US008362376B2

(12) **United States Patent**
Sen et al.

(10) **Patent No.: US 8,362,376 B2**
(45) **Date of Patent: Jan. 29, 2013**

(54) **ELECTROSTATICALLY DRIVEN HIGH SPEED MICRO DROPLET SWITCH**

(75) Inventors: **Prosenjit Sen**, Los Angeles, CA (US); **Chang-Jin Kim**, Beverly Hills, CA (US)

(73) Assignee: **The Regents of the University of California**, Oakland, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 660 days.

(21) Appl. No.: **12/523,419**

(22) PCT Filed: **Jan. 15, 2008**

(86) PCT No.: **PCT/US2008/051094**
§ 371 (c)(1),
(2), (4) Date: **Jul. 16, 2009**

(87) PCT Pub. No.: **WO2008/147576**
PCT Pub. Date: **Dec. 4, 2008**

(65) **Prior Publication Data**

US 2010/0025207 A1 Feb. 4, 2010

Related U.S. Application Data

(60) Provisional application No. 60/885,826, filed on Jan. 19, 2007.

(51) **Int. Cl.**
H01H 29/00 (2006.01)
(52) **U.S. Cl.** **200/182**
(58) **Field of Classification Search** 200/182
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,323,447 B1 11/2001 Kondoh et al.
6,559,420 B1 5/2003 Zarev
6,946,776 B2 * 9/2005 Fong et al. 310/328
7,005,593 B2 2/2006 Gasparyan et al.
7,030,328 B1 4/2006 Beerling
7,132,614 B2 11/2006 Beerling
7,271,688 B1 9/2007 Beerling et al.

FOREIGN PATENT DOCUMENTS

WO WO 2006/057780 A2 6/2006
WO WO 2006/068744 A2 6/2006

(Continued)

OTHER PUBLICATIONS

PCT International Preliminary Report on Patentability (Chapter I of the Patent Cooperation Treaty) for PCT/US2008/051094, Applicant: The Regents of the University of California, Form PCT/IB/326 and 373, dated Jul. 30, 2009 (6 pages).

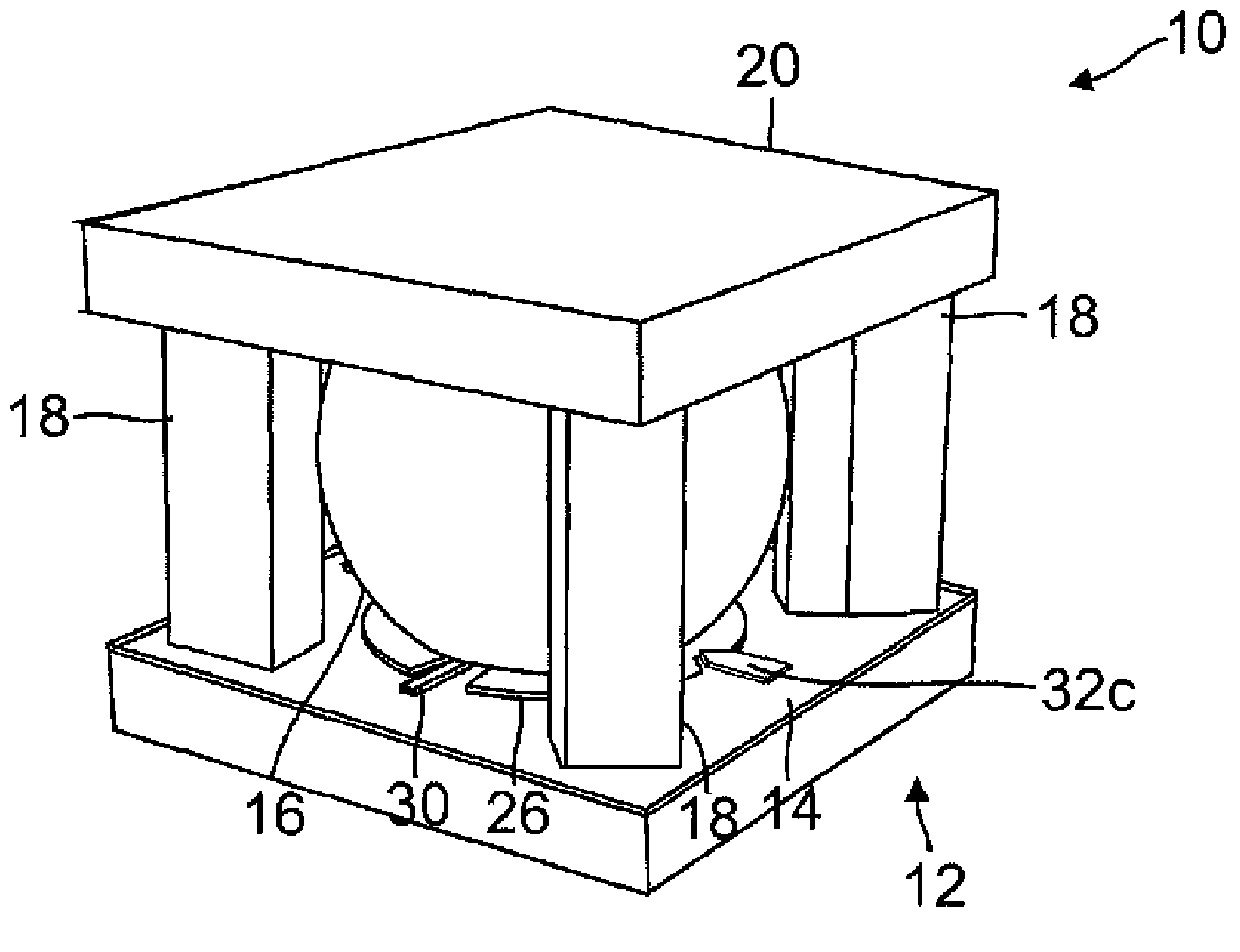
(Continued)

Primary Examiner — Renee Luebke
Assistant Examiner — Lheiren Mae Caroc
(74) *Attorney, Agent, or Firm* — Vista IP Law Group LLP

(57) **ABSTRACT**

An electrostatically driven high-speed micro droplet switch includes a substrate having an upper surface containing one or more signal electrodes that are selectively connected via a droplet. The switch includes at least one actuation electrode disposed beneath the upper surface of the substrate, the at least one actuation electrode operatively coupled to drive circuitry. The switch includes a frame disposed on or above the upper surface of the substrate that is configured to hold the droplet in substantially the same location during operation of the switch. In one aspect, the frame is configured to absorb variations in the volume of the droplet placed on the switch, leaving the active meniscus not affected by the variation in volume.

28 Claims, 11 Drawing Sheets



FOREIGN PATENT DOCUMENTS

WO	WO 2006/118703	A1	11/2006

OTHER PUBLICATIONS

Kim, J. et al., A Micromechanical Switch with Electrostatically Driven Liquid-Metal Droplet, Proc. Int. Conf. Solid-State Sensors and Acutators (Transducers '01), Jun. 2001, Munich, Germany, pp. 748-751.

Edwards, R.T. et al., Breaking the Resistivity Barrier, Proc. The 3rd NASA/Dod Workshop on Evolvable Hardware, Jul. 2001, Pasadena, CA, pp. 167-171.

Kim, J. et al., A Micromechanical Switch with Electrostatically Driven Liquid-Metal Droplet, Sensors and Actuators, vol. A97-98, pp. 672-679, 2002.

Shen, W. et al., Controlling the Adhesion Force for Electrostatic Actuation of Microscale Mercury Drop by Physical Surface Modification, IEEE 2002, pp. 52-55.

Shen, W. et al., Mercury Droplet Microswitch for Re-Configurable Circuit Interconnect, Proc. Int. Conf. Solid State Sensors, Actuators and Microsystems (Transducers '03), Boston, Jun. 8-12, 2003, pp. 464-467.

Shen, W. et al. Fabrication, Packaging and Charaterization of Mercury Droplet Switches Integrated on CMOS Chip, Presented at ASME Int. Mechanical Engineering Congress and Exposition, Anaheim, CA, Nov. 2004; pp. 1-6.

Sen, P. et al., Electrostatic Fringe-Field Actuation for Liquid-Metal Droplets, Proc. Int. Conf. Solid State Sensors, Actuators and Microsystems (Transducer '05), Seoul, Korea, Jun. 2005, pp. 705-705.

Shen, W. et al., Electrostatically Actuated Metal-Droplet Microswitches Integrated on CMOS Chip, Journal of Microelectromechanical System, vol. 15, No. 4, Aug. 2006, pp. 879-889.

Sen, P. et al., A Fast Liquid-Metal Droplet Switch Using EWOD, IEEE Conf. MEMS, Kobe, Japan, Jan. 2007, pp. 767-770.

PCT International Search Report for PCT/US2008/051094, Applicant: The Regents of the University of California, Form PCT/ISA/210 and 220, dated Sep. 18, 2008 (4 pages).

PCT Written Opinion of the International Search Authority for PCT/US2008/051094, Applicant: The Regents of the University of California, Form PCT/ISA/237, dated Sep. 18, 2008 (6 pages).

* cited by examiner

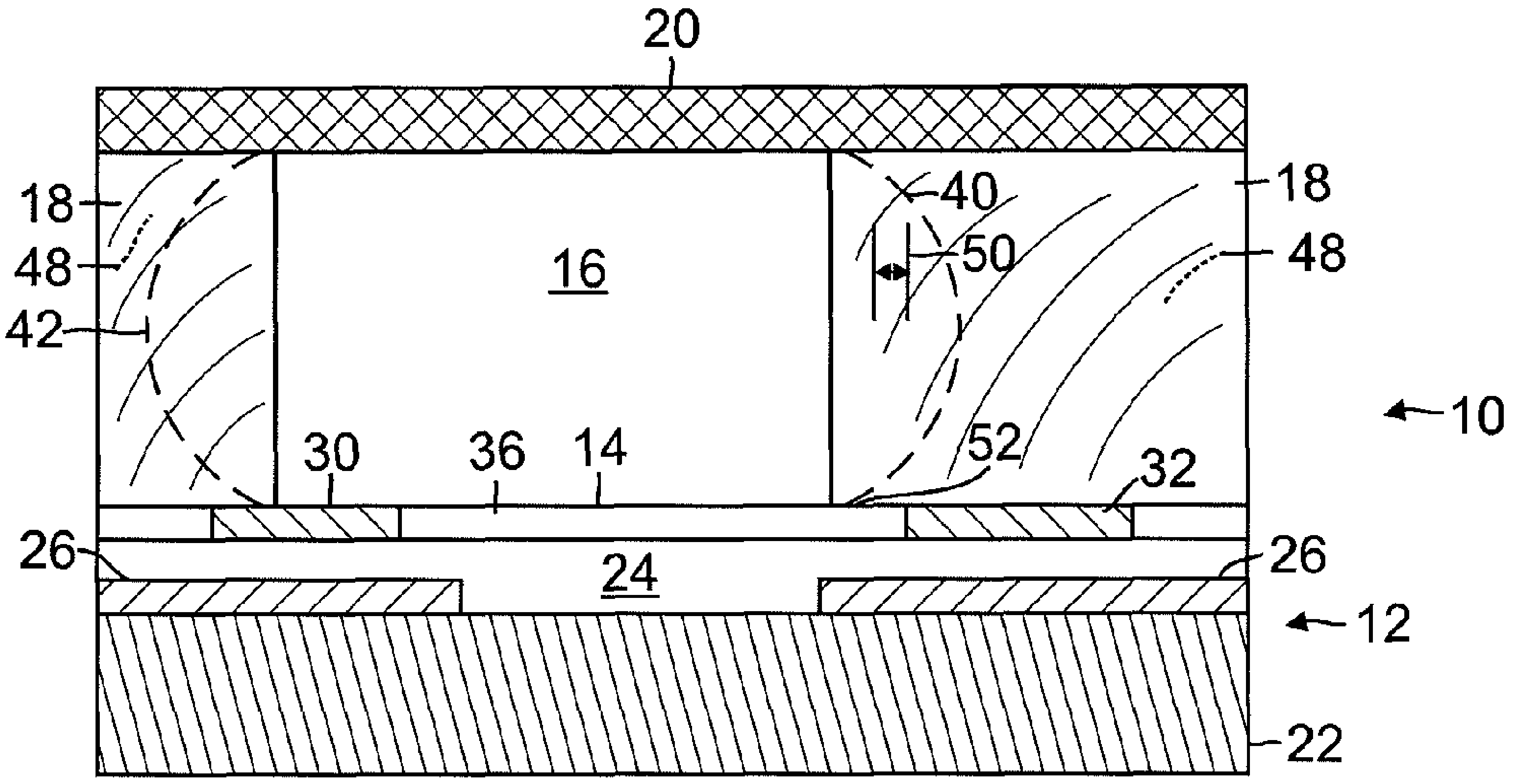

20
18
48
42
16
40
50
18
48
10
30
36
14
52
32
26
24
26
12
22

FIG. 1A

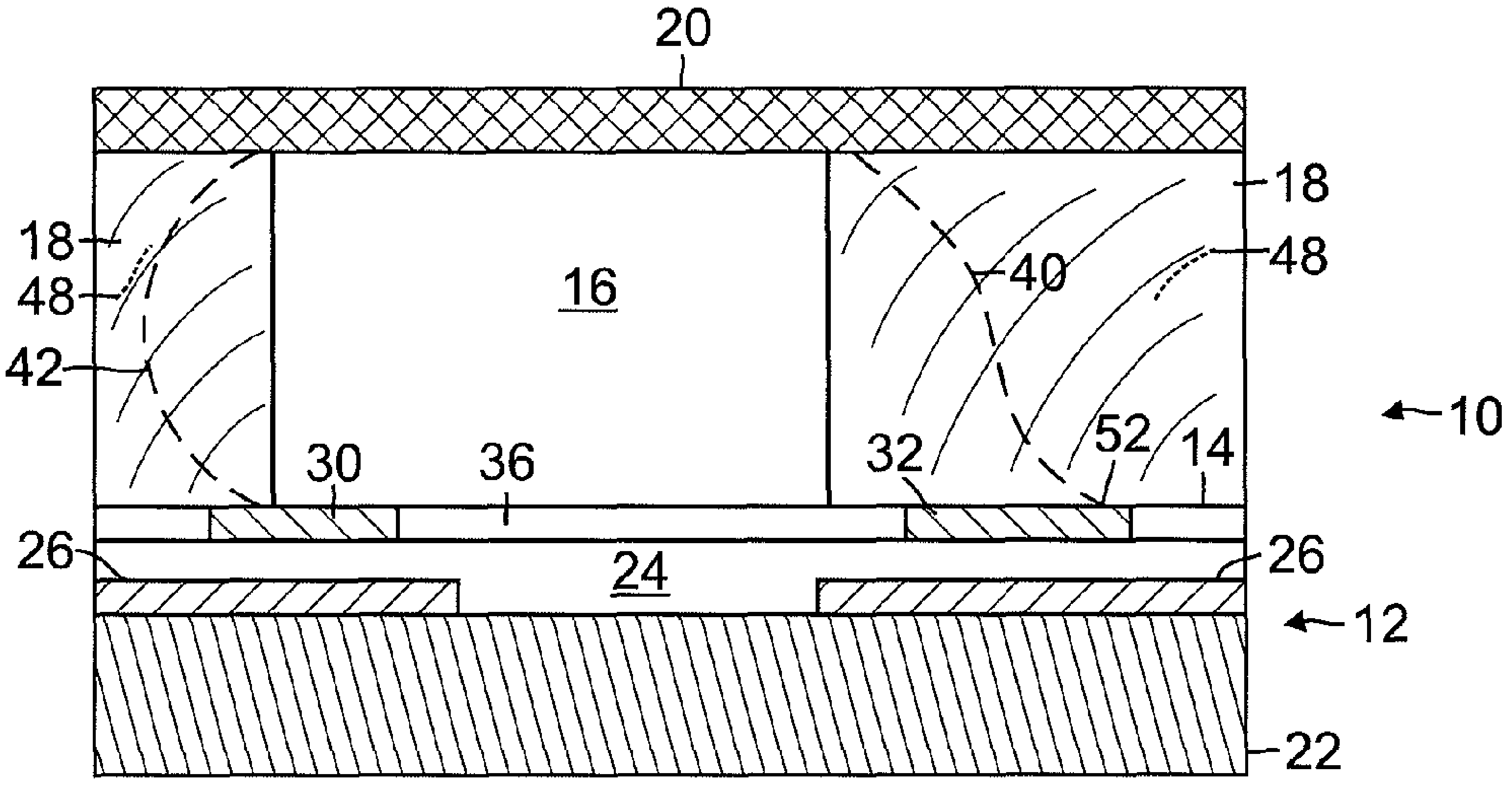

20
18
48
42
16
40
18
48
10
30
36
32
52
14
26
24
26
12
22

FIG. 1B

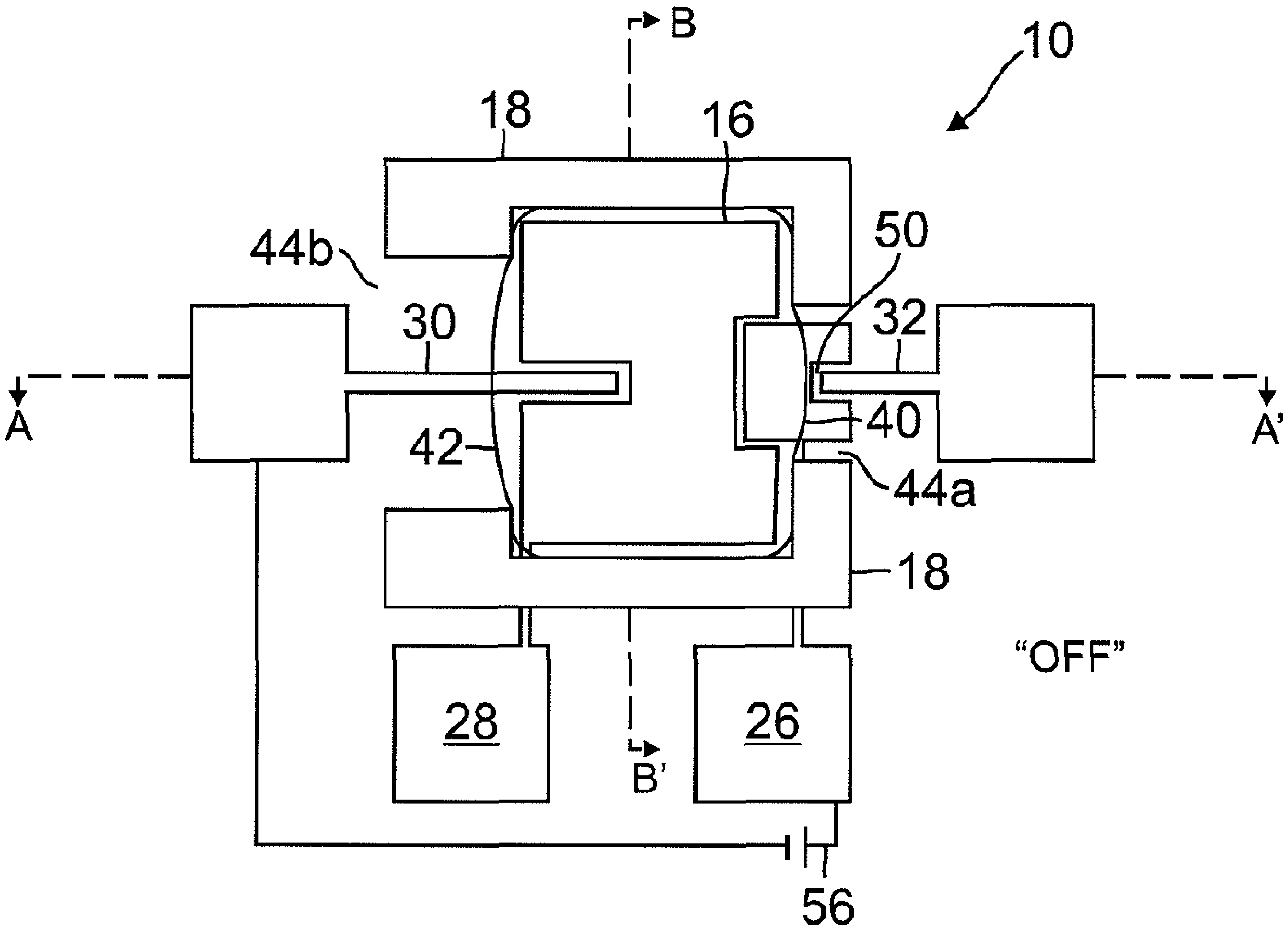

B
10
18
16
44b
50
30
32
A
40
A'
42
44a
18
"OFF"
28
26
B'
56

FIG. 2A

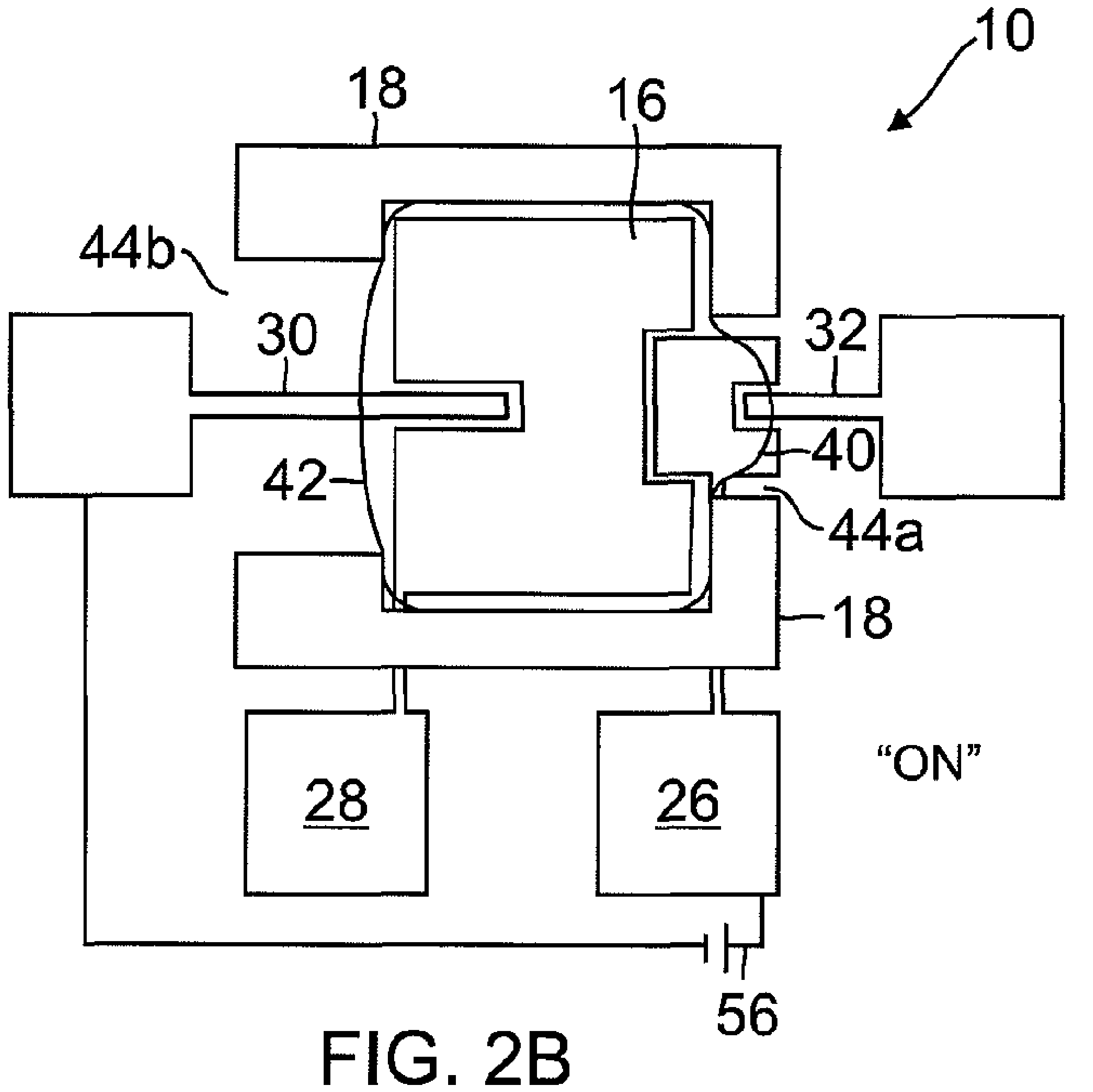

10
18
16
44b
30
32
40
42
44a
18
"ON"
28
26
56

FIG. 2B

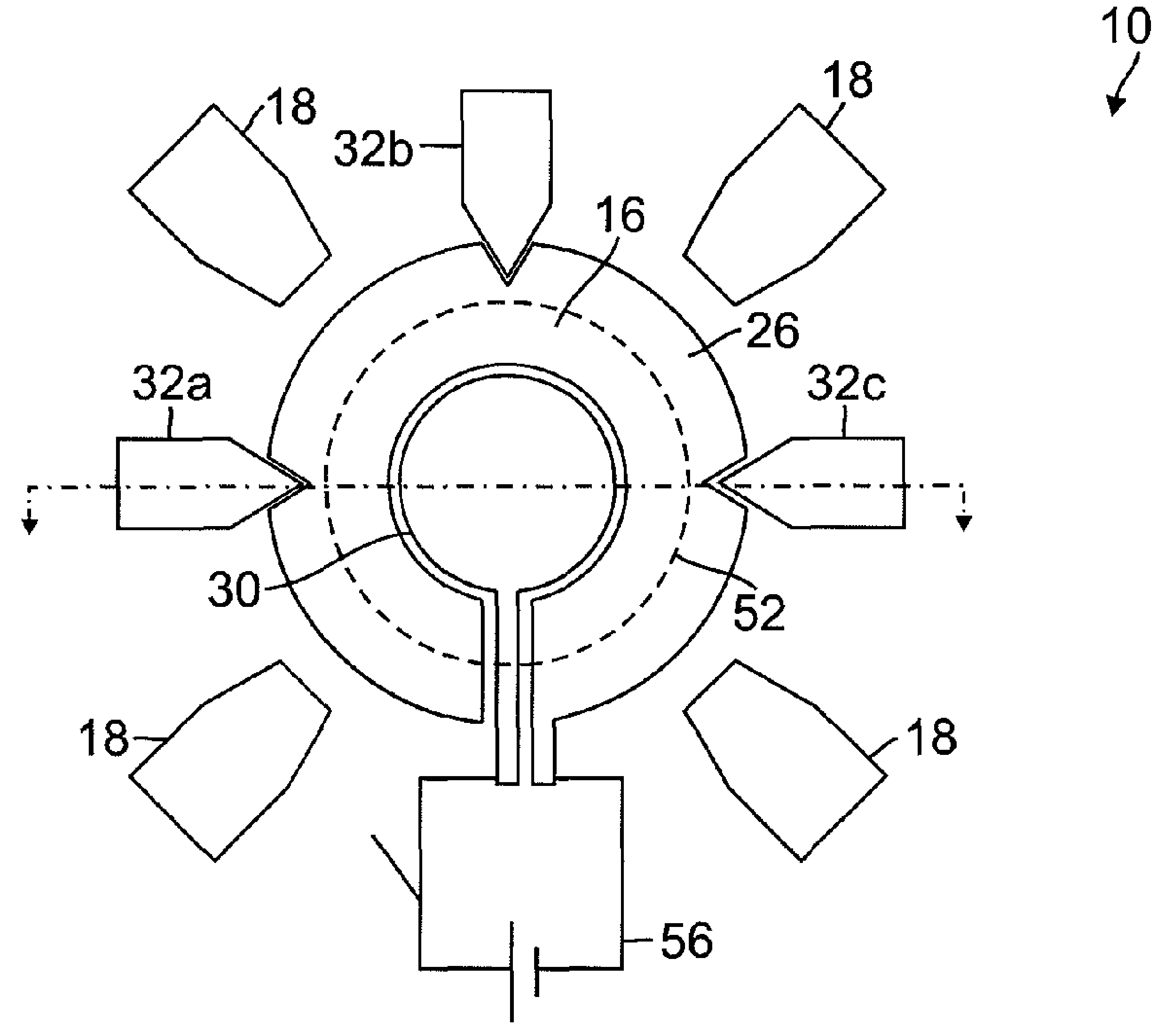

10
18
32b
18
16
26
32a
32c
30
52
18
18
56

FIG. 3A

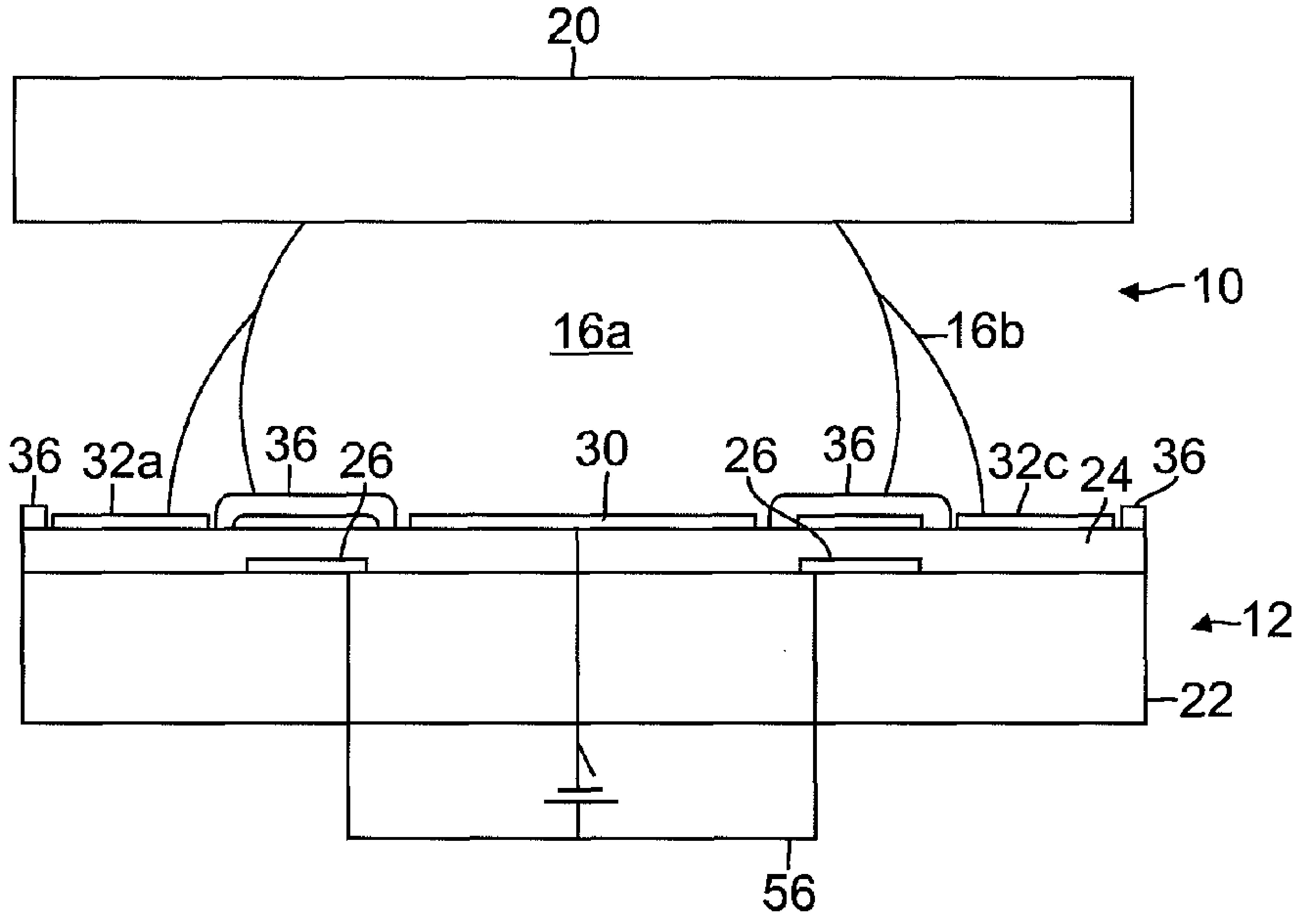

20
10
16a
16b
36
32a
36
26
30
26
36
32c
24
36
12
22
56

FIG. 3B

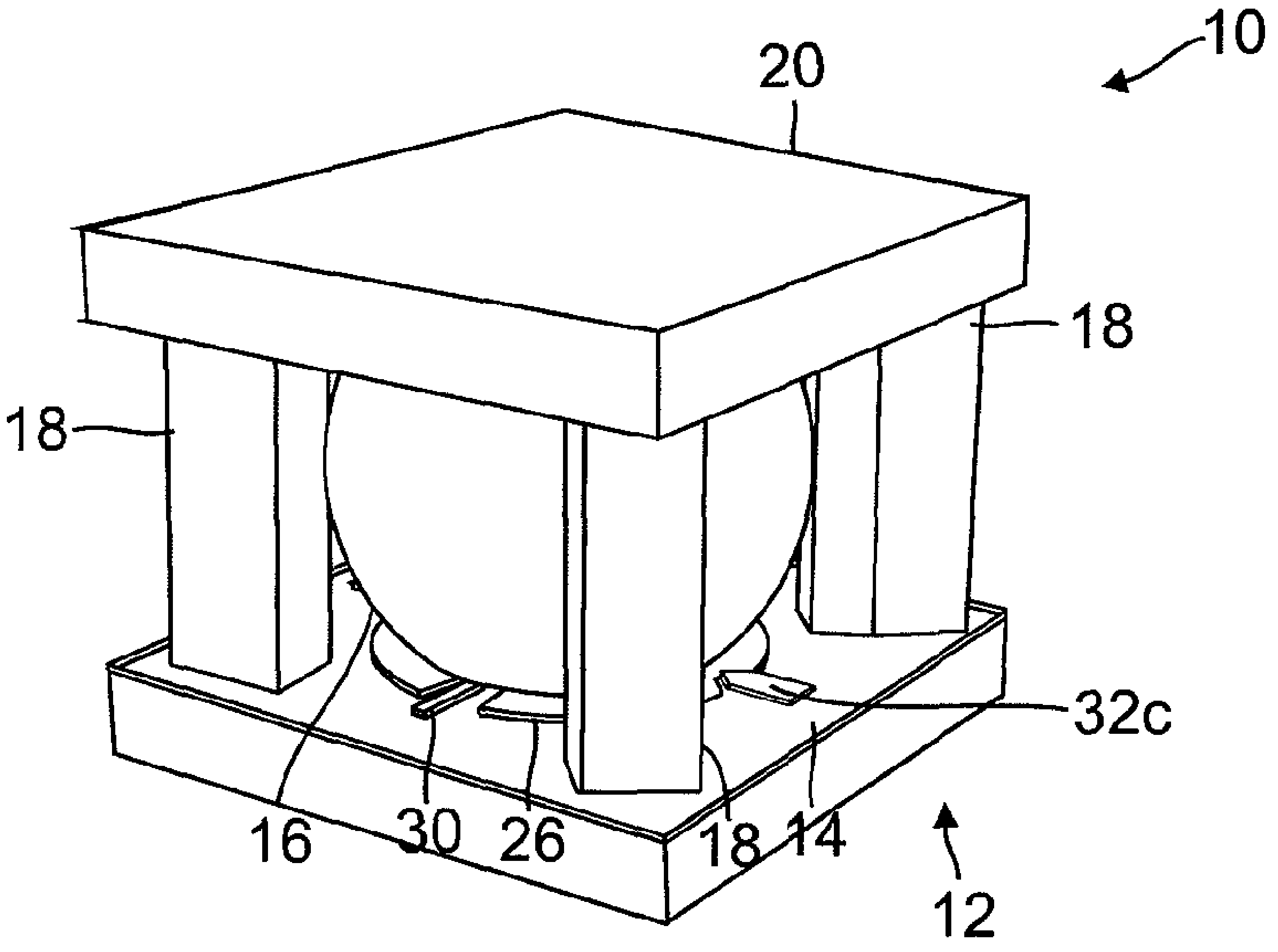

10
20
18
18
32c
16
30
26
18
14
12

FIG. 3C

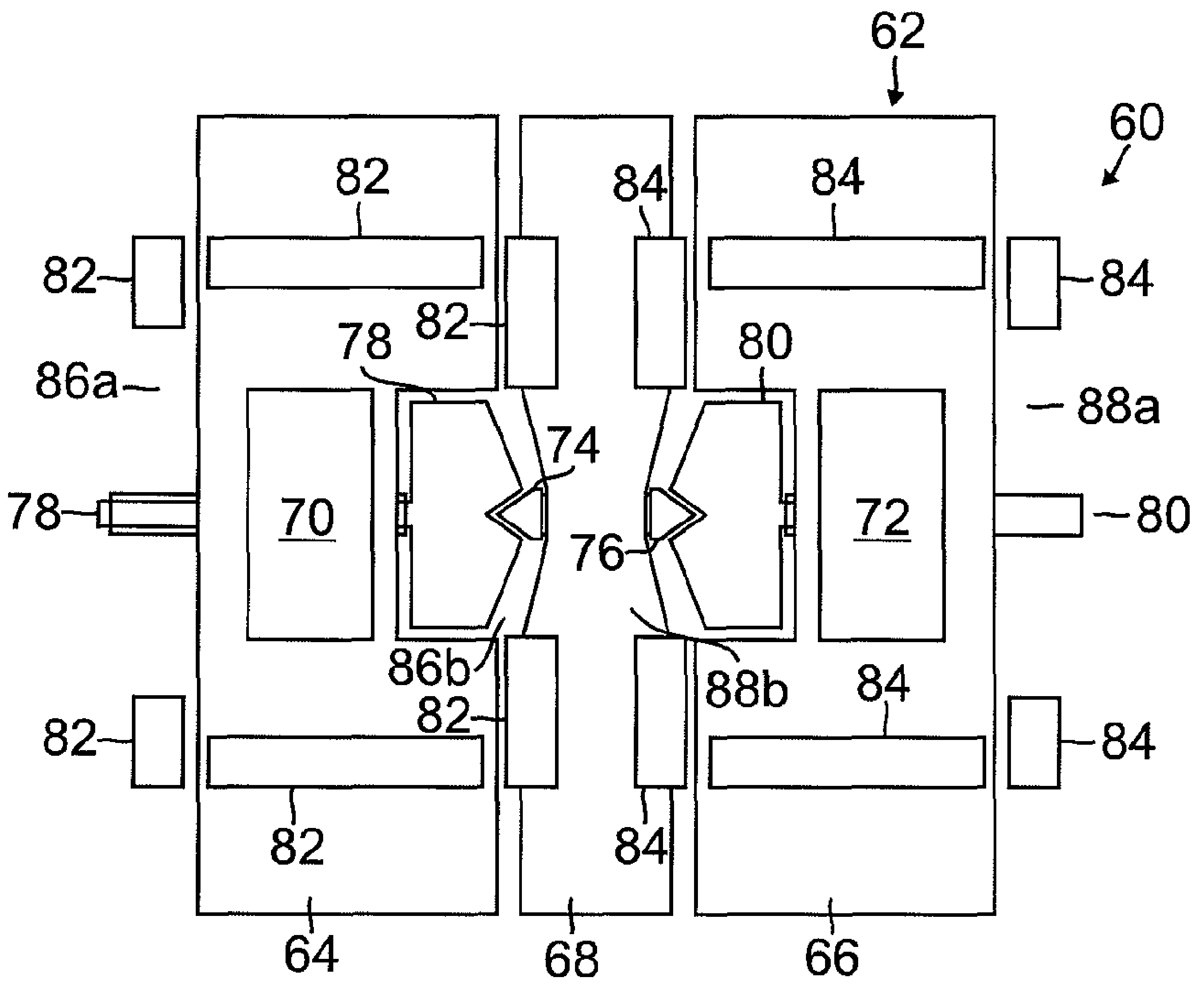

62
60
82
84
84
82
84
82
78
80
86a
88a
74
78
70
72
80
76
86b
88b
84
82
82
84
82
84
64
68
66

FIG. 4A

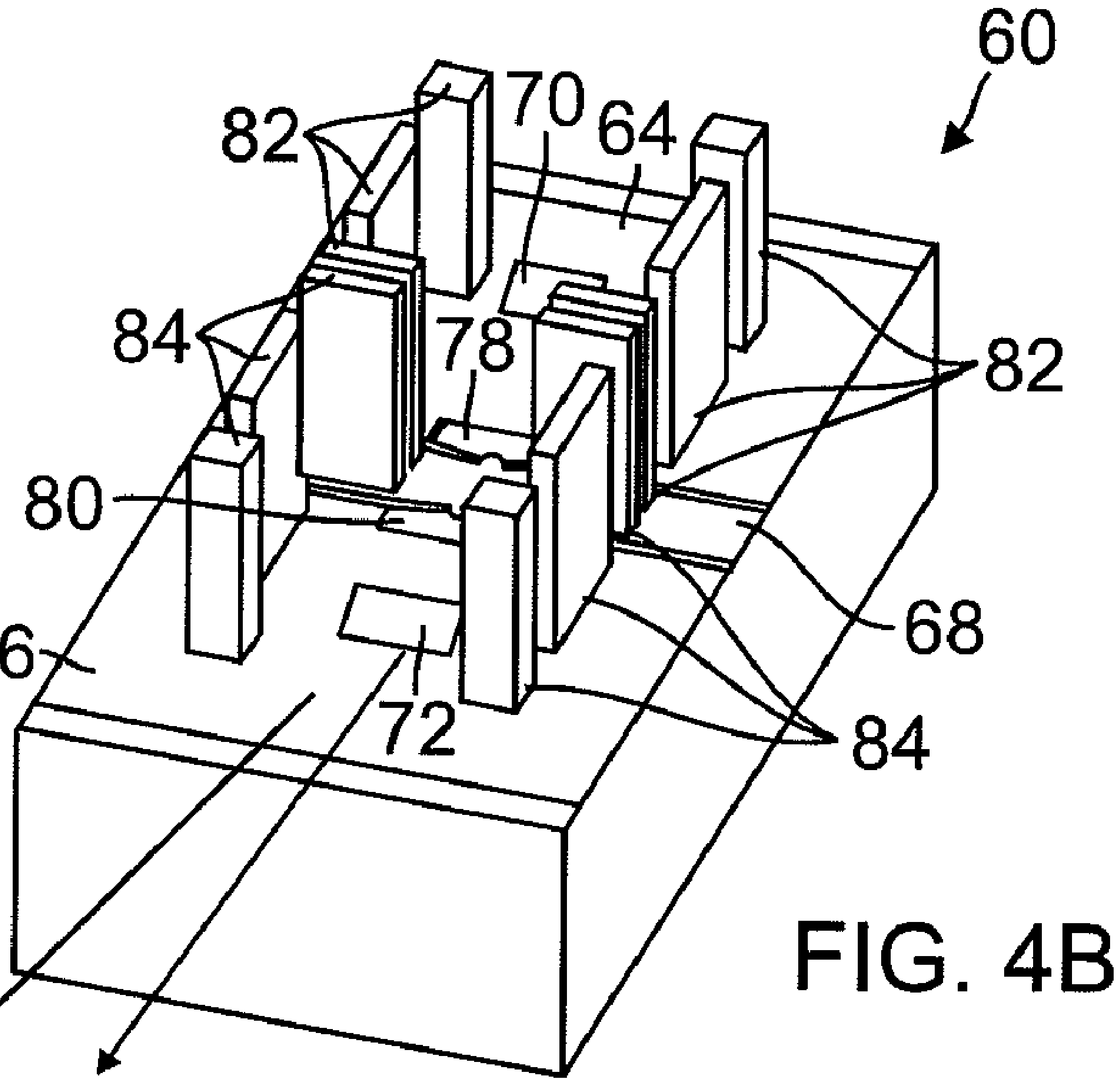


FIG. 4B

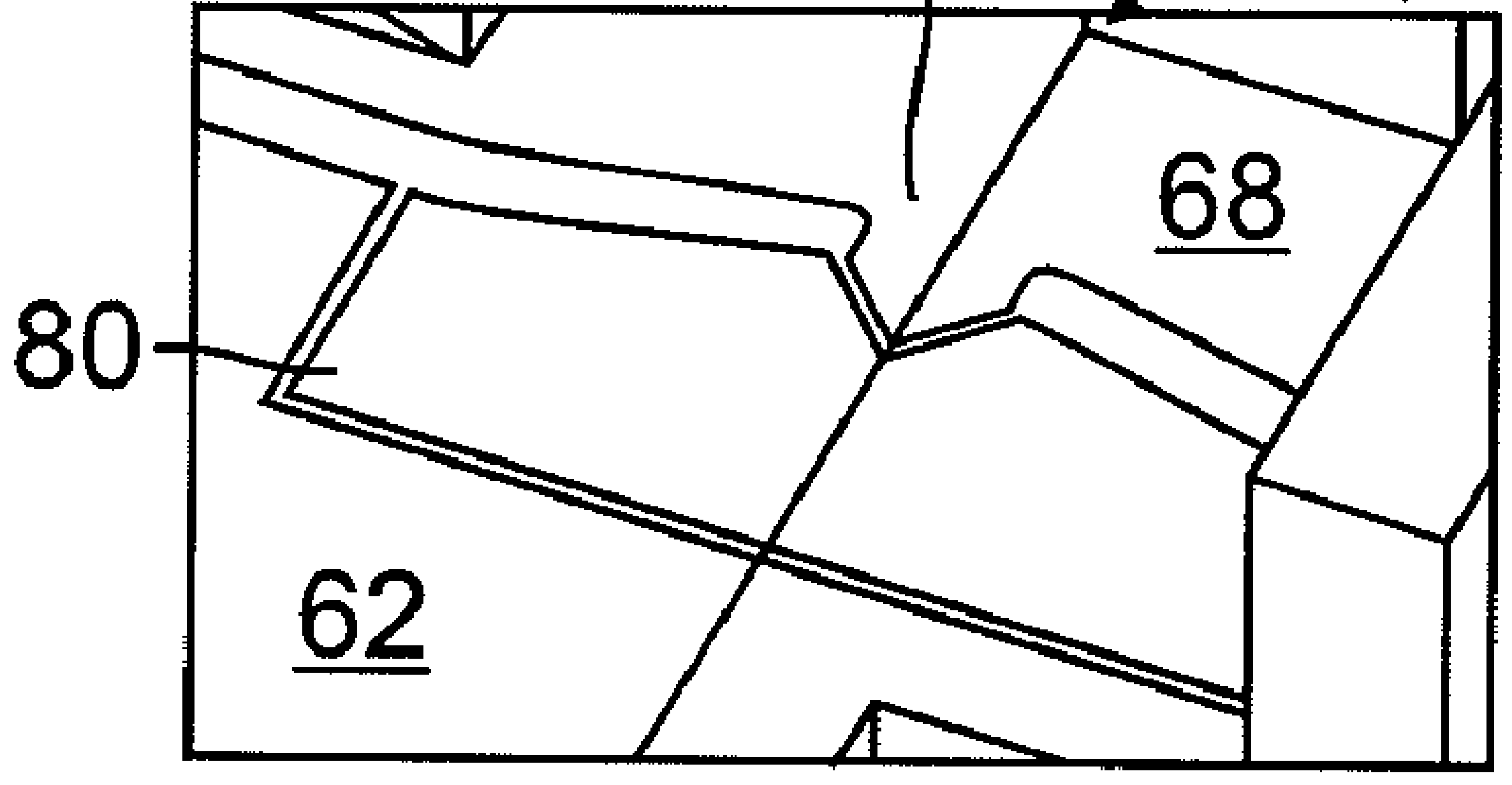


FIG. 4C

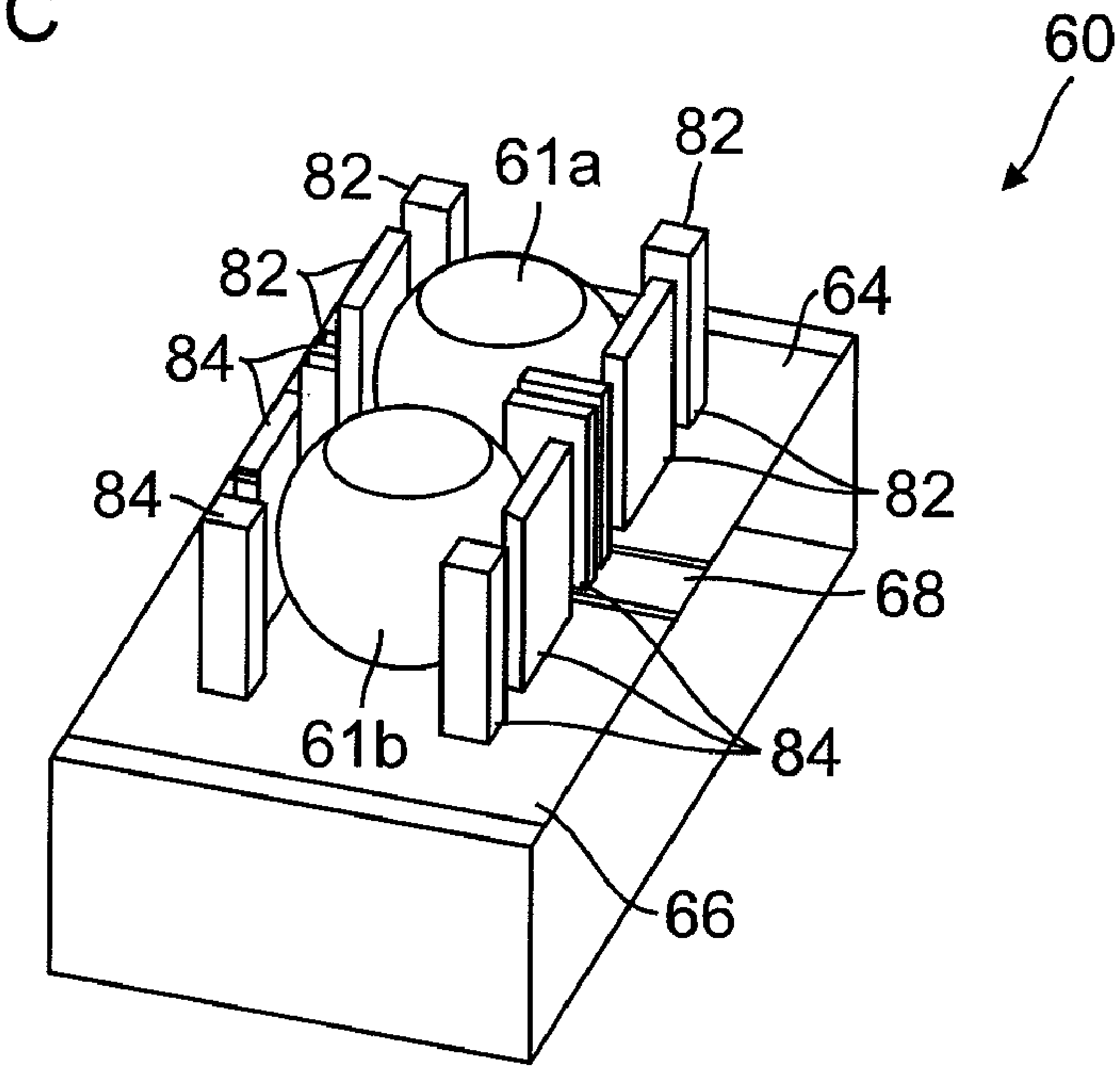


FIG. 4D

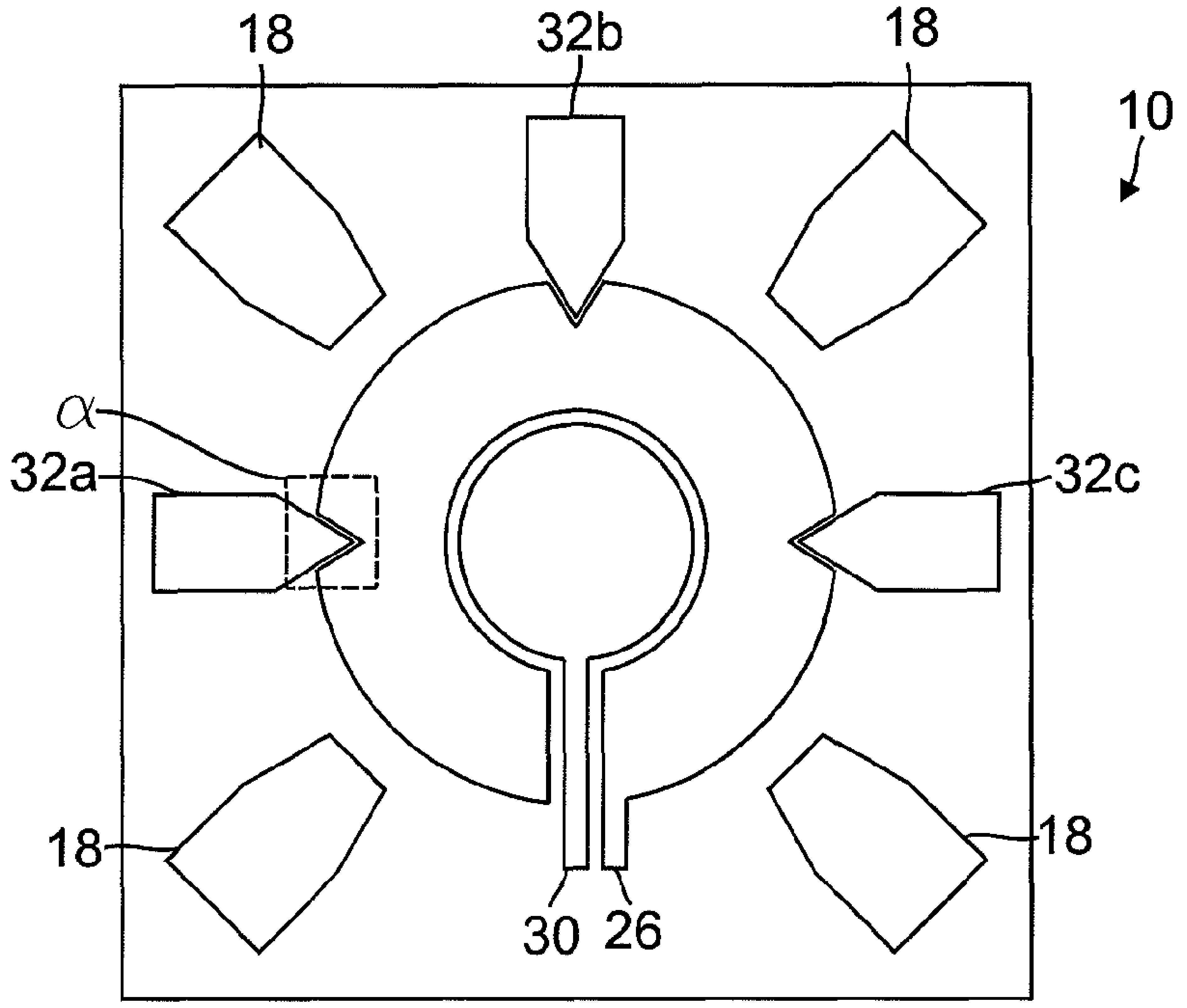


FIG. 5A

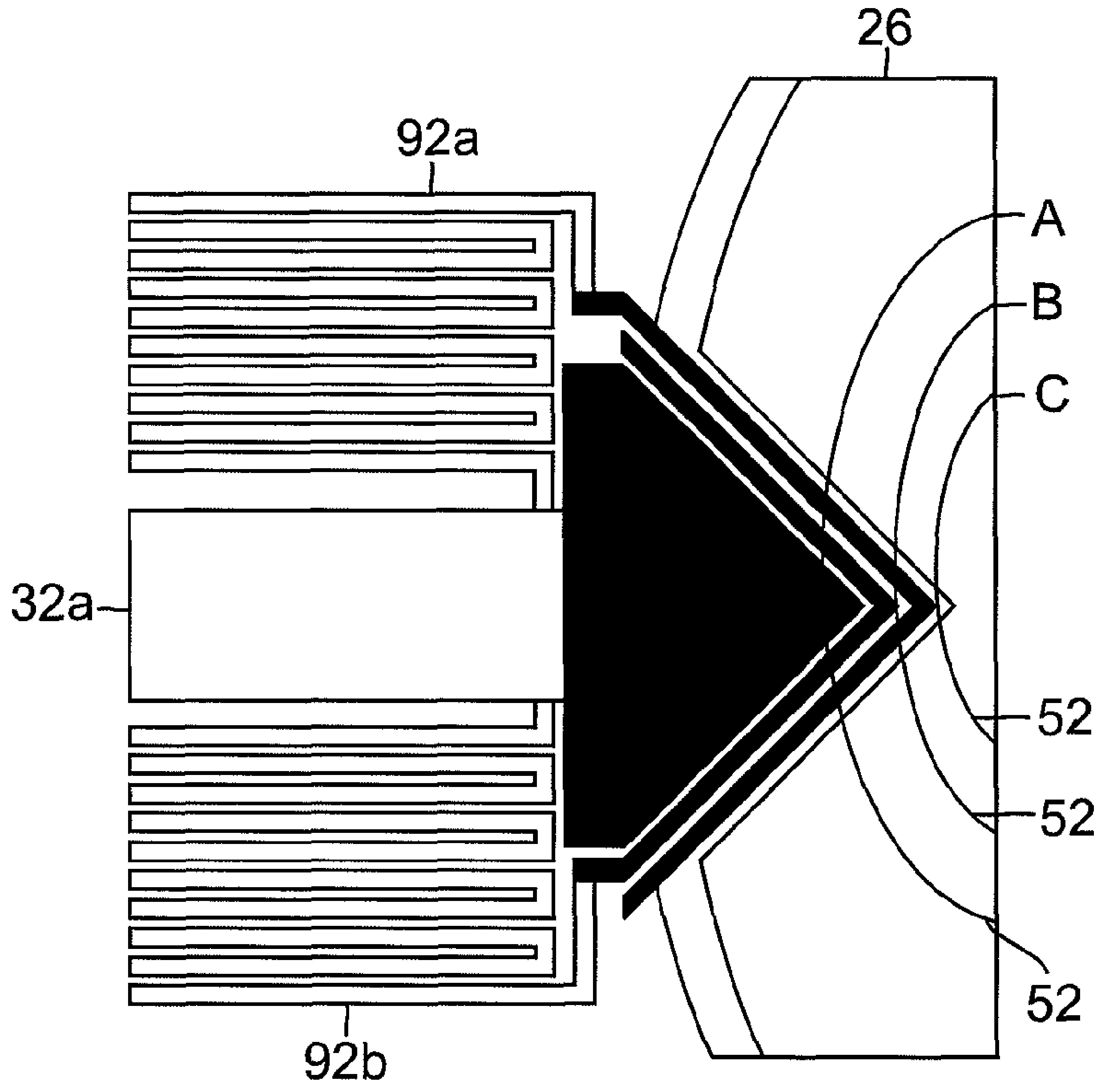


FIG. 5B

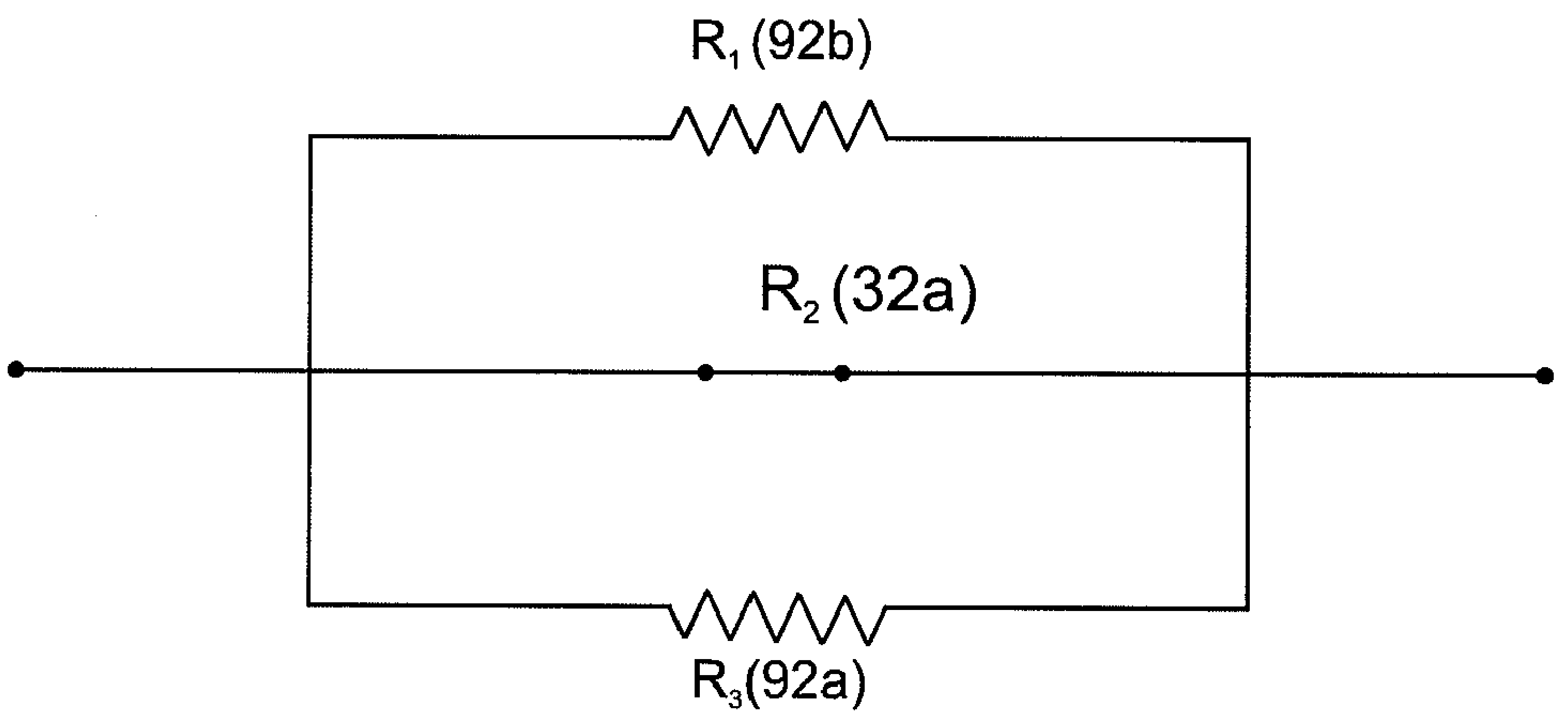


FIG. 6A

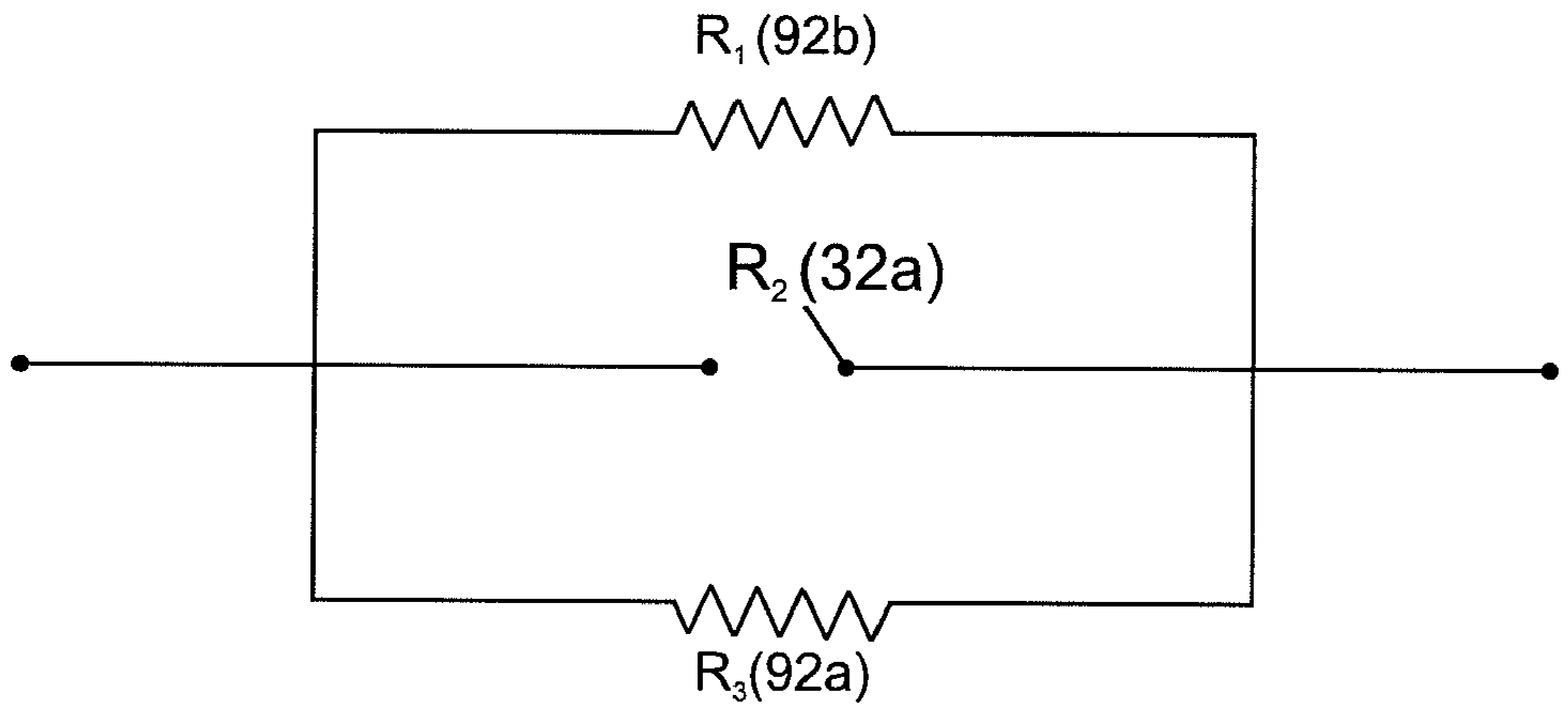


FIG. 6B

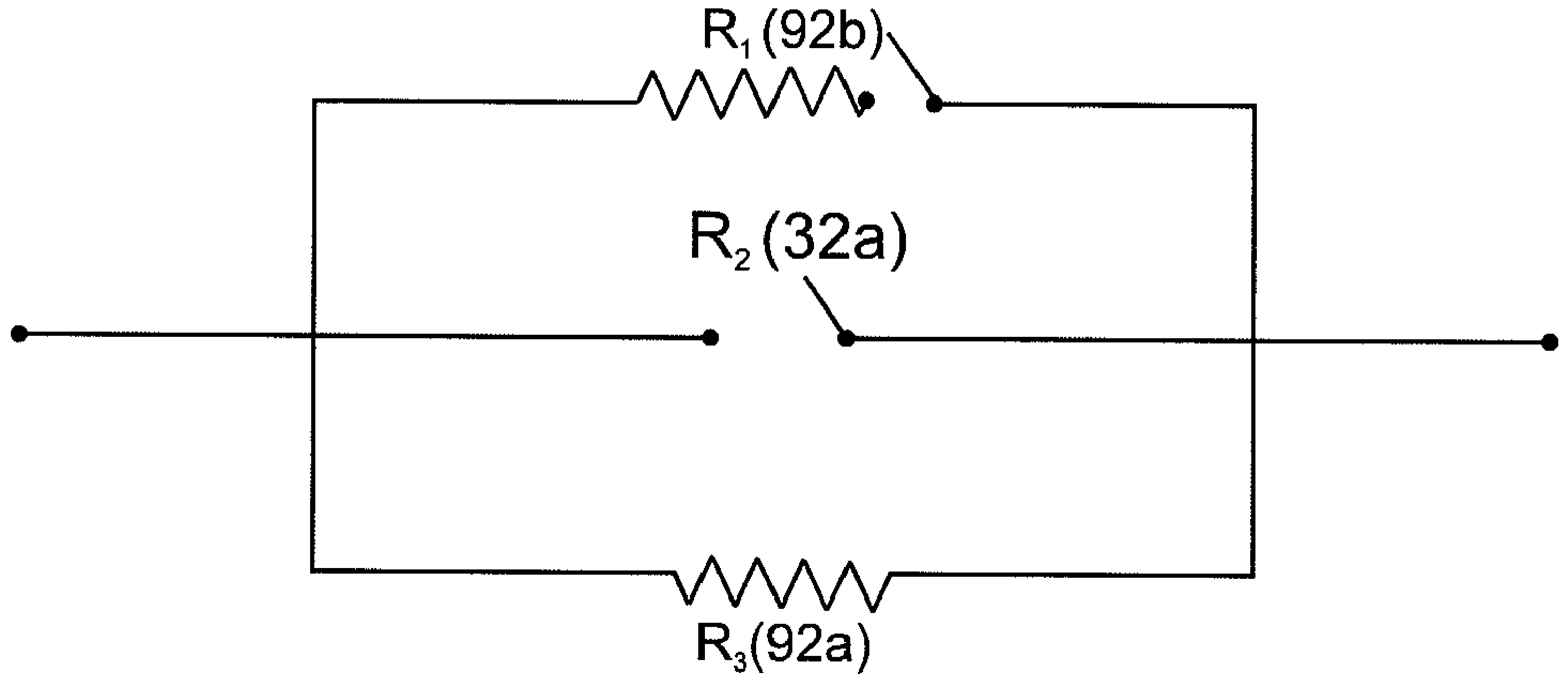


FIG. 6C

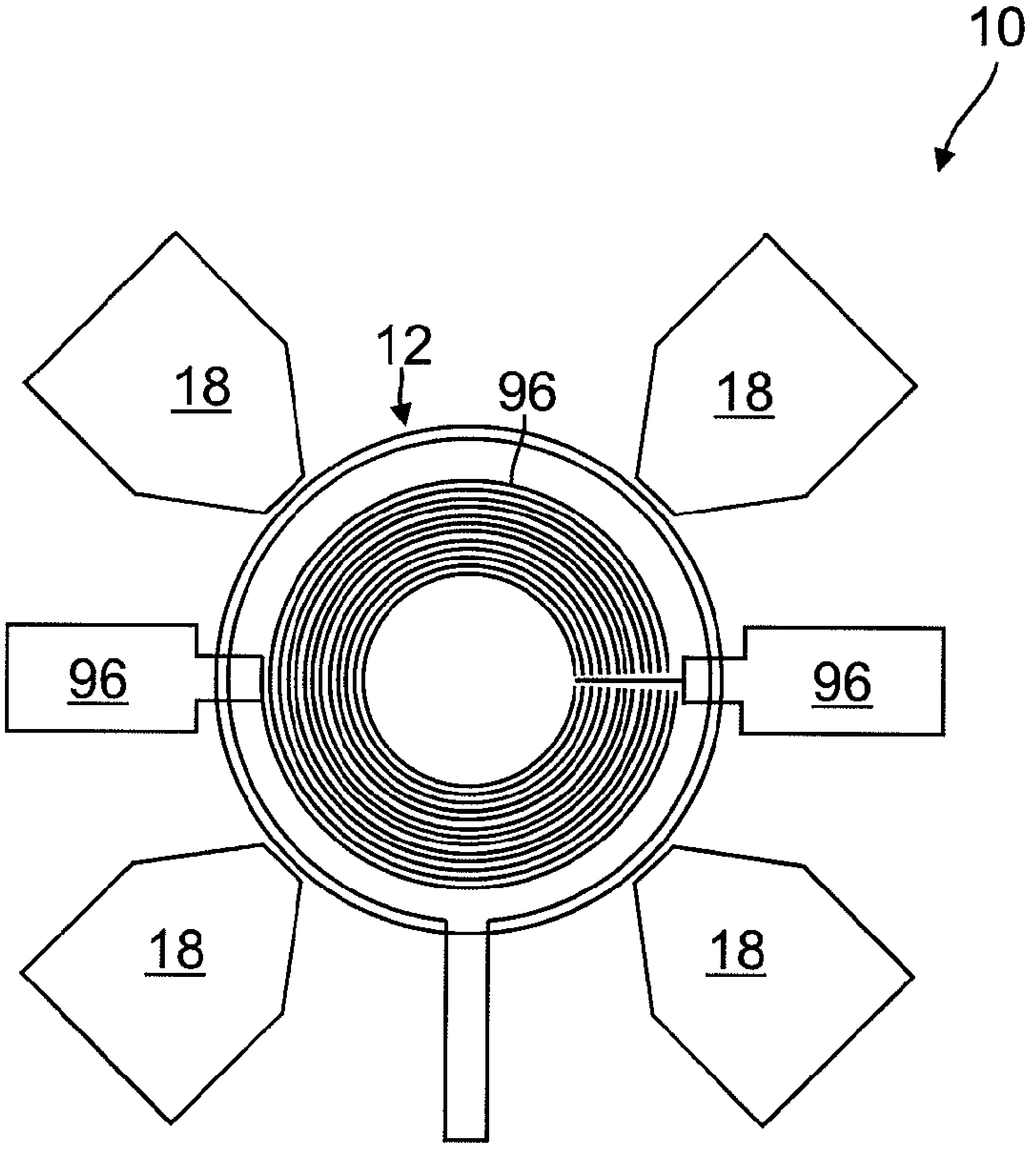


FIG. 7

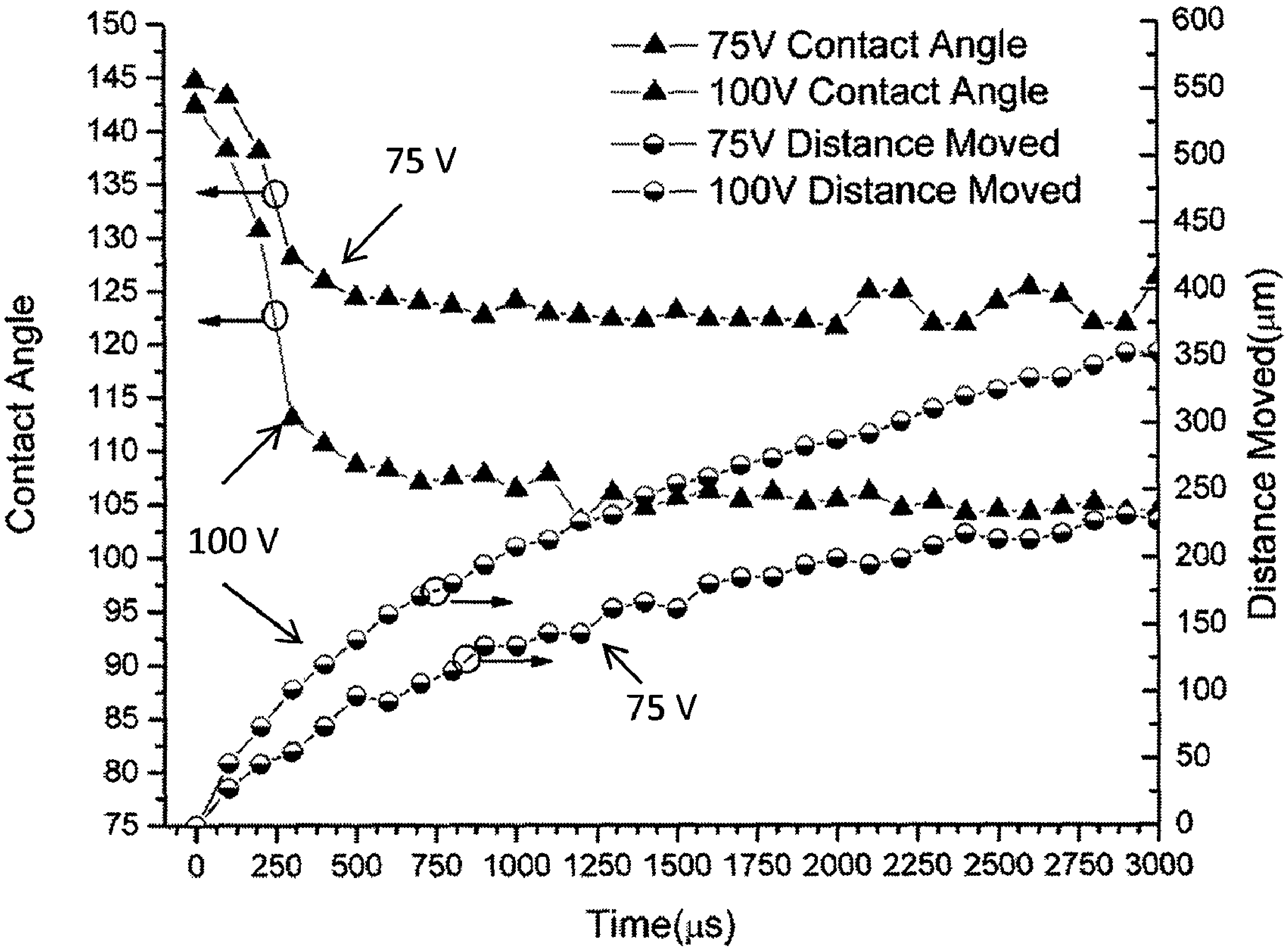

150
145
140
135
130
125
120
115
110
105
100
95
90
85
80
75
Contact Angle
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000
Time(μs)
600
550
500
450
400
350
300
250
200
150
100
50
0
Distance Moved(μm)
75V Contact Angle
100V Contact Angle
75V Distance Moved
100V Distance Moved
75 V
100 V
75 V

FIG. 8

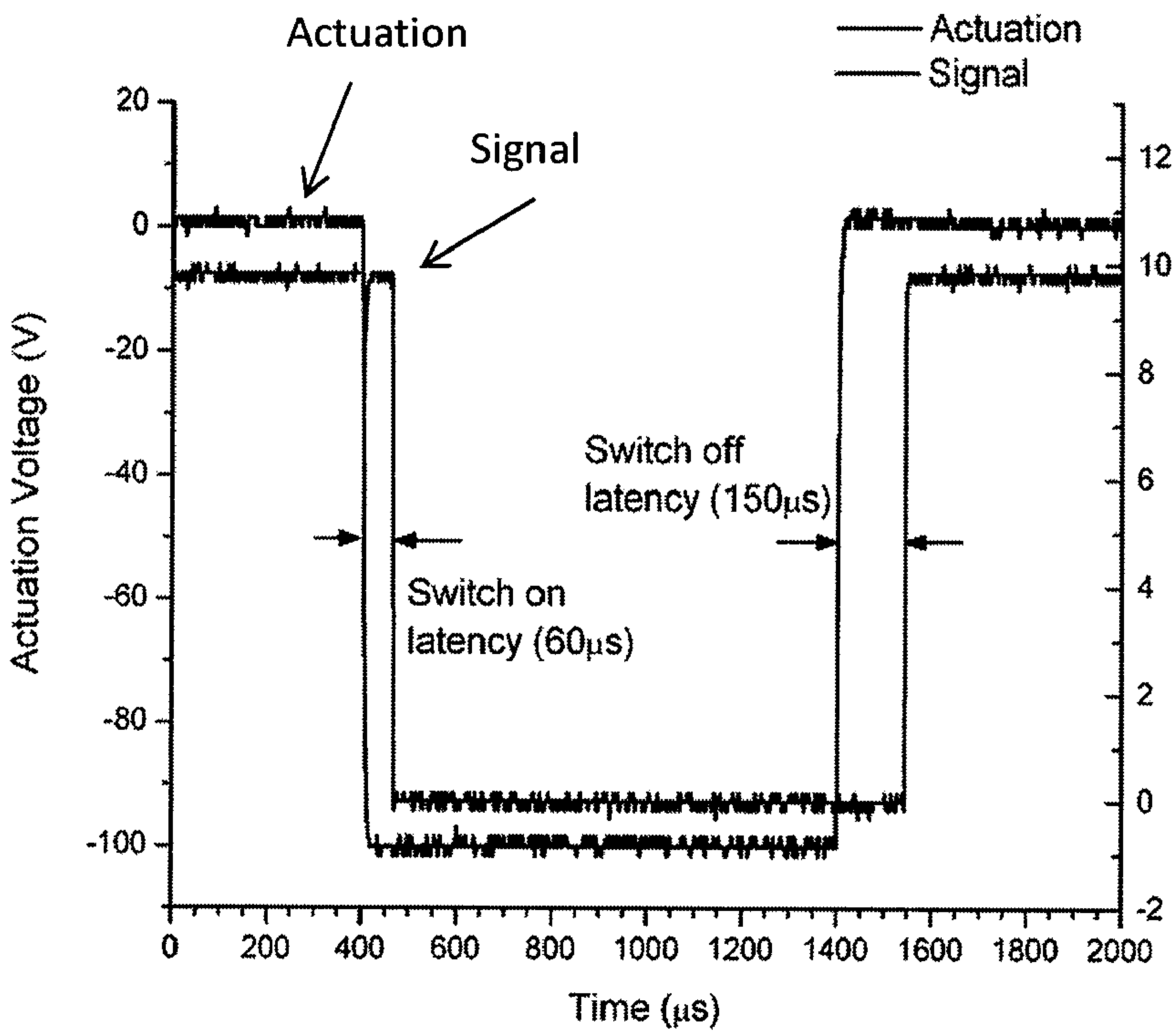

Actuation
Signal
Actuation
Signal
Actuation Voltage (V)
20
0
-20
-40
-60
-80
-100
Signal Voltage (V)
12
10
8
6
4
2
0
-2
Switch off latency (150μs)
Switch on latency (60μs)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Time (μs)

FIG. 9A

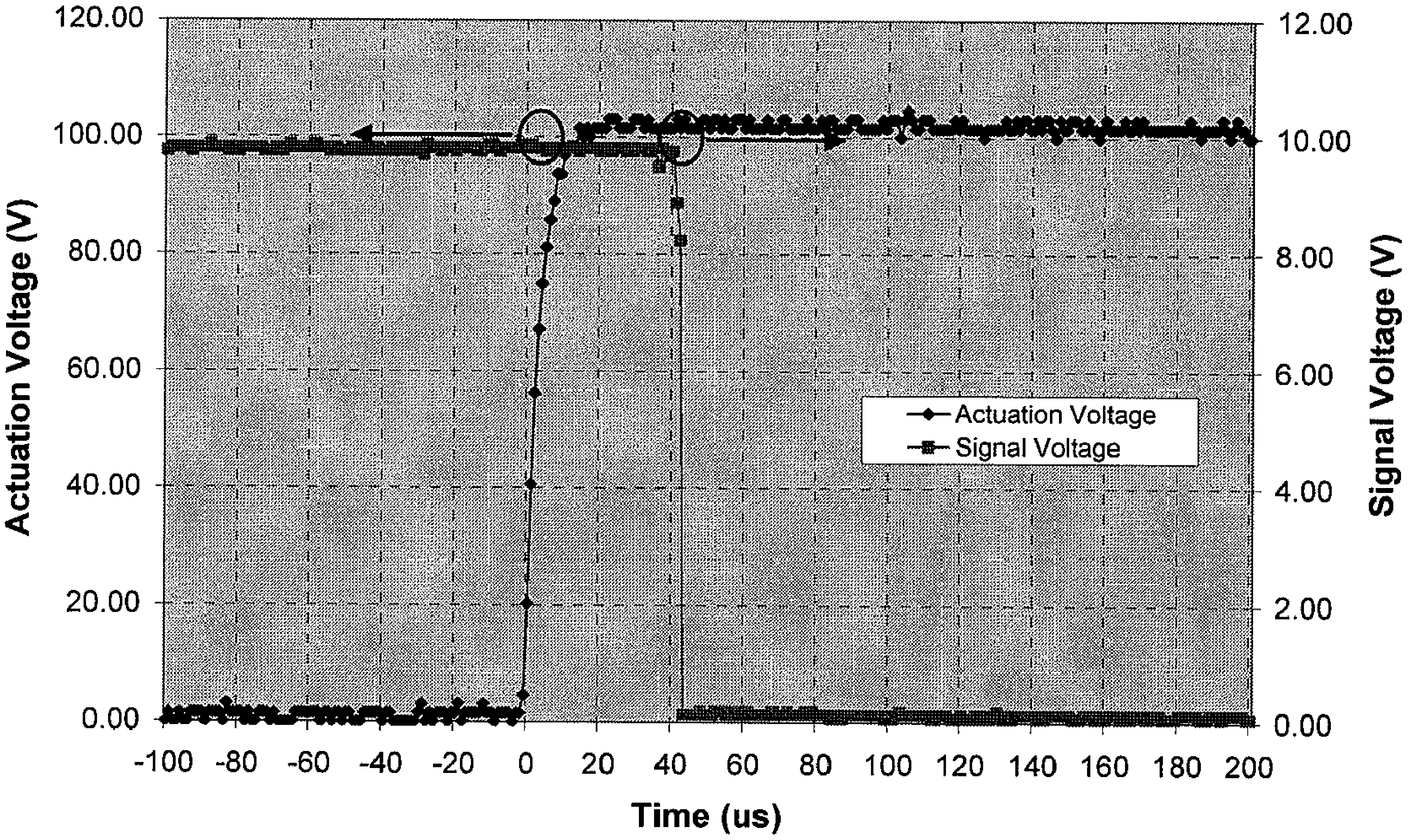

Actuation Voltage (V)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Signal Voltage (V)
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Actuation Voltage
Signal Voltage
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
180
200
Time (us)

FIG. 9B

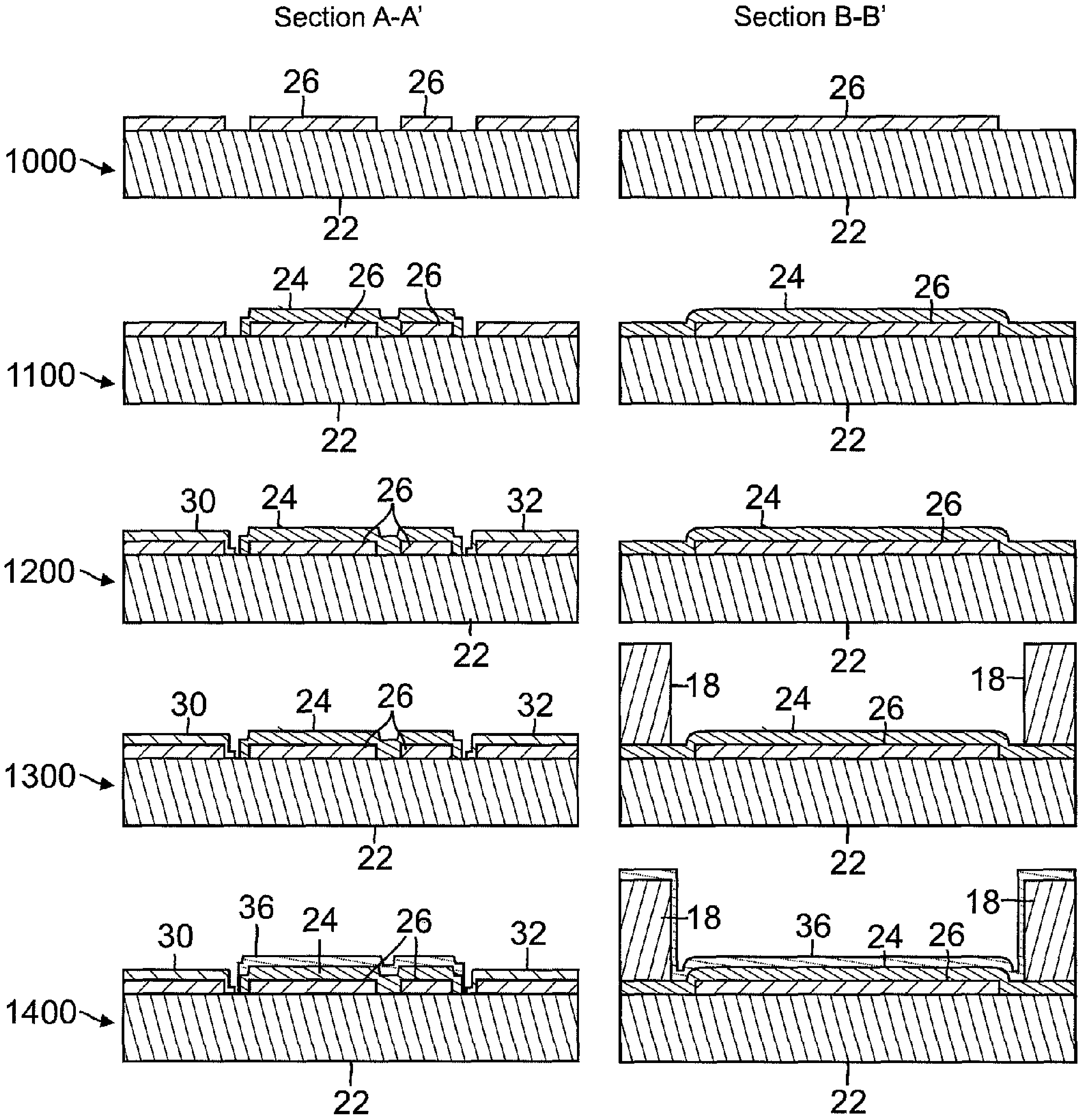

Section A-A'
Section B-B'
26
26
26
1000
22
22
24
26
26
24
26
1100
22
22
30
24
26
32
24
26
1200
22
22
18
18
30
24
26
32
24
26
1300
22
22
18
18
36
24
26
30
32
36
24
26
1400
22
22

FIG. 10

ELECTROSTATICALLY DRIVEN HIGH SPEED MICRO DROPLET SWITCH

REFERENCE TO RELATED APPLICATIONS

This Application is a U.S. National Stage filing under 35 U.S.C. §371 of International Application No. PCT/US2008/051094, filed Jan. 15, 2008, which claims priority of U.S. Provisional Patent Application No. 60/885,826 filed on Jan. 19, 2007. The contents of the aforementioned applications are incorporated by reference as if set forth fully herein. Priority to the aforementioned application is hereby expressly claimed in accordance with 35 U.S.C. §§119, 120, 365 and 371 and any other applicable statutes.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

This invention was made with Government support under Grant No. N66001-05-1-8908 and N66001-07-01-2027 awarded by the Department of the Navy. The Government has certain rights in this invention.

FIELD OF THE INVENTION

The field of the invention generally relates to micro switches and in particular micromechanical switches. More particularly, the field of the invention relates to micro liquid-metal switches.

BACKGROUND OF THE INVENTION

Conventional semiconductor transistors are well known in their ability to provide high speed switching capability in a relatively inexpensive and small size. Conventional semiconductor-based transistors do, however, suffer from various problems that are not present in mechanical microswitches. Mechanical switches, moreover, include many promising properties that semiconductor transistors lack. For example, micromechanical switches can be built to have a very high "off" resistance and a low "on" resistance resulting in lower loss and less power dissipation. This feature is particularly advantageous because certain applications (e.g., radio frequency applications) require higher electrical isolation between components. Another advantage offered by mechanical switches is that they are more linear and stable with respect to a wide variety of operating conditions such as voltage, current, temperature, pressure, and radiation.

Various micro-electrical-mechanical (MEMS) switches have been proposed and developed for switching applications. Despite the variations in detailed designs and actuation methods, almost all the MEMS-based microswitches utilize microscale beam structures. These types of microswitches operate with solid-to-solid contact between elements, sharing many typical problems of macroscale mechanical switches such as surface degradation (leading to an increase in the contact resistance) and signal bounce effects during switch actuation.

The use of conductive droplet systems has been proposed to overcome these limitations, liquid metals being the droplet material for most applications. In these systems, a metallic droplet such as mercury is physically moved by typically an electrical actuation toward a contact element in a microswitch. The droplet systems generally offer low contact resistance, linear responses, and long lifetimes. Unfortunately, existing droplet-based microswitches have limited application because of the slower switching speeds. An important aspect of the switching speed is switch latency, referring to the amount of time that elapses between actuation of the switch and the closing of the switch. In the case of droplet microswitches, the closing is effectuated by droplet movement. Consequently, their latency tends to be larger (slower) than that of the solid beam-based micro switches and much slower than that of semiconductor switches. In these metallic droplet systems, the lowest reported latency period is on the order of 1 millisecond. See e.g., W. Shen et al., Electrostatically Actuated Metal-Droplet Microswitches Integrated on CMOS Chip, J. MEMS, Vol. 14, No. 4, August 2006, pp. 879-889. There thus is a need for metal-droplet microswitches that have faster switching rates. For example, switching rates at or below around 100 μs (micro seconds) would enable microswitches to be used in many more applications such as, for instance, RF switches and dynamic displays. Such switches would have high performance characteristics of, for instance, high durability, low resistance, no signal bounce, in addition to the high speed switching capability that has heretofore been unrealized in existing metal-droplet switches.

SUMMARY OF THE INVENTION

The speed at which a given micro droplet switch can operate is a function of several parameters including the speed at which the droplet travels and the distance it must travel before making contact with a signal electrode (e.g., to close the switch). While the known practice is to move the droplet, or move the center of mass of the droplet to express exactly, toward the signal electrode, the present invention keeps the droplet substantially stationary and instead moves (i.e., spreads) only the droplet contact line toward the signal electrode. As used herein, the droplet contact line refers to the peripheral interface between the droplet used in the microswitch and the substrate on which the droplet is placed. To accommodate the new type of micro droplet switch disclosed herein, the speed at which a given micro droplet switch can operate is a function of several parameters including the speed at which the droplet contact line can travel as well as the distance the contact line must travel before making contact with a signal electrode.

In order to achieve high speed movement of the contact line, a large actuation force may be used to a certain degree, after which it is limited by other fundamental complications as well as practical design challenges. In order to achieve small distance to travel, the droplet contact line should be placed as close as possible to the signal electrode reliably. Unfortunately, the droplet cannot be formed, deposited, or defined by standard photolithographic semiconductor fabrication techniques, forcing one to use much larger switching gaps. The challenges of placing the droplet contact line on an exact location originate from the difficulties in: (1) accurately positioning the droplet on the switch, (2) depositing a droplet with an accurate volume or size, and (3) positioning and keeping the contact line on the exact location against physical disturbances and surface conditions. For example, considering (1) and (2) above, conventional droplet deposition techniques are problematic because it is difficult, if not impossible, to deposit the correct volume of droplet material on the precise location, when compared with the sub-micrometer accuracies the lithographic techniques allows for the rest of features on the microdevice. If too much droplet material is deposited, even on the exact location on the switch, the actuation gap (the distance to travel for the droplet contact line) may narrow too much or be inadvertently closed without actuation. Overall, there is a need to maintain a substantially constant actuation gap between the contact line of the droplet and the signal electrode.

The micro droplet switch described herein solves the above-identified deficiencies by providing a frame structure that places the droplet on a location accurately defined by the frame fabrication method. After the droplet placement, the frame further restricts unwanted free motion of the droplet on the surface of the micro switch. In this regard, during operation of the microswitch, the droplet remains in substantially the same location—there is no bulk or translational movement of the entire droplet as in other micro droplet switch devices. The frame structure is also designed, in one aspect of the invention, to produce a buffering meniscus in the non-active portion of the droplet. The buffering meniscus is able to buffer variations in the volume of the droplet that is applied to the micro droplet switch. In this regard, the buffering meniscus accepts the excess or deficiency in fluid volume so as to leave the active meniscus substantially unmodified. In one aspect of the invention, the buffering meniscus is formed by a frame that has a larger opening or aperture at one end while a smaller opening or aperture at the other end. The smaller opening in the frame is used to create the active meniscus while the larger opening in the frame is used to create the buffering meniscus. As a result, the buffering meniscus facilitates the maintenance of the tight tolerance required for the actuation gap between the active meniscus of the droplet and the signal electrode. This length of the actuation gap is also maintained over many cycles of switching, thus giving repeatable control over operation of the device.

By using the spreading of the droplet contact line rather than the movement of the entire body of the droplet, a switching can be completed fast. In addition, the small operation distance permits very high switching frequencies. For example, as explained herein, switching latencies of around 50 μs may be obtained with the microswitch described herein which is some 20× faster than other liquid metal droplet switches. See e.g., W. Shen et al., Electrostatically Actuated Metal-Droplet Microswitches Integrated on CMOS Chip, J. MEMS, Vol. 14, No. 4, August 2006, pp. 879-889 (switching latency on the order of 1 millisecond). Moreover, the microswitch described herein is rugged and provides a high degree of stability against shock and vibrations (~16 G).

In one embodiment, a micro droplet switch includes a substrate having an upper surface containing a contact electrode and a separate signal electrode. For example, the contact electrode may comprise an input electrode while the signal electrode may comprise an output electrode. In one aspect the contact electrode may include one of a plurality of signal electrodes. For example, the switch may be closed by the droplet contacting two signal electrodes, one of which is the contact electrode. As explained below, the switch is closed when the droplet electrically connects the contact electrode to the signal electrode. In one aspect of the invention, the droplet may always be in contact with the contact electrode and is selectively engaged with the signal electrode. The micro droplet switch includes at least one actuation electrode disposed beneath the upper surface of the substrate. The at least one actuation electrode is coupled to the drive circuitry for applying a voltage to the actuation electrode. Typically, the at least one actuation electrode is located within or below or layer of dielectric material forming the substrate. The upper surface of the substrate (with the exception of the contact electrode and the signal electrode) may be coated with an insulative, hydrophobic coating such as polytetrafluoroethylene (PTFE). The micro droplet switch includes a frame that is disposed on or above the surface of the substrate and is configured to hold a droplet in substantially the same location during actuation of the switch. In this regard, the frame restricts unwanted free motion of the droplet.

The droplet is a conductive liquid and may be made of a liquid metal such as, for instance, mercury. When placed on the upper surface of the substrate, the interface between the droplet and the surface forms a contact line. This contact line moves in response to actuation of the at least one actuation electrode based on known electrowetting-on-dielectric (EWOD) principles. Generally, in EWOD-based devices, the liquid droplet spreads by modification of the surface tension in response to electrostatic charges induced at the liquid-metal interface of the droplet. When the activation electrode is not activated, the shape of the droplet is restored. While other liquid droplet based devices have relied on EWOD actuation for the bulk movement of droplets, the present micro droplet switch does not rely on the bulk or translational movement of the entire droplet to effectuate switching between a contact electrode and the signal electrode. As explained herein, the use of the frame maintains the droplet in substantially the same location during actuation of the switch.

The frame may be disposed at a predetermined location relative to the signal electrode. In this regard, the switching gap between the contact line of the droplet and the signal drop may be controlled by the design of the frame. The frame may be manufactured using conventional lithographic processes used in the fabrication of semiconductor features. The frame ensures that a substantially constant gap is formed between the contact line of the droplet (in the non-actuated state) and the signal electrode. This gap may be a distance of less than 100 μm or even less than 5-20 μm.

The frame may include multiple openings having different sizes in order to form a buffering meniscus. In this embodiment, the frame includes a first opening that contains or is adjacent to the active meniscus of the droplet. This is the portion of the droplet that undergoes movement to complete the electrical connection between the contact electrode and the signal electrode. The frame also includes a second opening that contains or is adjacent to the non-active meniscus of the droplet. This second opening is larger than the first opening and creates a buffering meniscus. The radius of curvature of the active meniscus is smaller than the radius of curvature of the buffering meniscus which results in the advantageous property that variations in the volume of the droplet are absorbed in the buffering meniscus. To wit, if too much or too little droplet material is deposited on the switch, the buffering meniscus adjusts accordingly, leaving the active meniscus substantially unaffected.

The switch may have multiple signal electrodes which may permit the switch to carry higher currents. In addition, in yet another alternative aspect of the invention, the switch may include one or more heating elements, which may be disposed beneath the upper surface of the substrate. The one or more heating elements may be configured to heat the substrate to remove charges that may have developed in the dielectric layer. The same or additional heating elements may also be used to heat the device during operation so that some metals that are not in a liquid state at room temperature (e.g., gallium) can be used. The heating elements may operate by resistive heating.

In another aspect of the invention, the signal electrode may include a plurality of resistive elements, wherein each resistive element is selectively engaged by the moving contact line during switch actuation. In this regard, the micro droplet switch may be made to have a stepped increase (or decrease) of resistance to reduce arcing when switching inductive loads. This aspect has particular applications when the micro droplet switch is used in "hot switching" inductive loads in RF switching applications.

The micro droplet switch described herein advantageously has fast switching times, for example, an "on latency" of less than about 50 μs. In addition, the switch has a rapid rise/fall time, for instance, less than about 5 μs. Further, these micro droplet switches do not suffer from signal bounce effects that may be found in other MEMS switches (e.g., beam switches). Finally, the use of the constraining frame structure makes these micro droplet switches particularly rugged and durable. For example, the micro droplet switches may exhibit vibrational stability of about to ~16 G.

In another embodiment of the invention, a switch is provided that includes two droplets contained within two frames. In this design the substrate is configured as a coplanar waveguide having a first ground portion, a signal portion, and a second ground portion (GSG design) in which the first and second ground portions include respective ground electrodes. The signal portion is operatively coupled to first and second signal electrodes. A first actuation electrode is disposed beneath the upper surface of the substrate adjacent to the first ground portion (e.g., the actuation electrode may be disposed beneath the upper surface of the substrate and in between the first ground electrode and the first signal electrode), the first actuation electrode being operatively coupled to drive circuitry. A second actuation electrode is disposed beneath the upper surface of the substrate adjacent to the second ground portion (e.g. the second actuation electrode may be disposed beneath the upper surface of the substrate and in between the second ground electrode and the second signal electrode), the second actuation electrode also being operatively coupled to drive circuitry. A first frame is disposed on or above an upper surface of the substrate and configured to hold a first droplet in substantially the same location over the first ground portion. A second frame is disposed on or above an upper surface of the substrate and configured to hold a first droplet in substantially the same location over the second ground portion. Actuation of the first and second actuation electrodes electrically connects the first droplet with the first signal electrode and electrically connects the second droplet with the second signal electrode. This two-droplet embodiment is advantageous because it eliminates signal leakage problems that appear in a single-droplet design for RF applications. This configuration is a shunt switch for RF applications.

In one aspect of the embodiment described immediately above, the first and second frames may have different sized openings to create the active meniscus and the buffering meniscus as described herein. For instance, the openings or apertures in the frame portions that define or are adjacent to the active meniscuses of the droplets are smaller than the openings or apertures in the frame portions that define or are adjacent to the buffering meniscuses of the droplets.

In still another aspect of the invention, a method of switching includes providing a micro droplet switch that includes a substrate having an upper surface containing a contact electrode and a separate signal electrode. The micro droplet switch includes at least one actuation electrode disposed beneath the upper surface of the substrate and operatively coupled to drive circuitry for applying a voltage. The micro droplet switch further includes a frame disposed on or above the upper surface of the substrate that is configured to hold a droplet, the droplet being in electrical contact with the contact electrode. The at least one actuation electrode is activated by applying a voltage to move a contact line of the droplet formed with the substrate surface in electrical contact with the signal electrode, wherein the droplet remains in substantially the same location during actuation of switch.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1**A is a cross-sectional view of a micro droplet switch according to one embodiment. FIG. **1**A illustrates the microswitch in an "off" state.

FIG. **1**B is a cross-sectional view of a micro droplet switch according to one embodiment. FIG. **1**B illustrates the microswitch in an "on" state.

FIG. **2**A illustrates a top down plan view of a micro droplet switch according to another embodiment. FIG. **2**A illustrates the microswitch in an "off" state.

FIG. **2**B illustrates a top down plan view of a micro droplet switch according to another embodiment. FIG. **2**A illustrates the microswitch in an "on" state.

FIG. **3**A illustrates a top down plan view of a micro droplet switch according to another embodiment. Drive circuitry is also illustrated.

FIG. **3**B illustrates a side view of the micro droplet switch of FIG. **3**A with the frames omitted for clarity purposes.

FIG. **3**C illustrates a three-dimensional perspective view of the micro droplet switch of FIGS. **3**A and **3**B with a droplet contained within the switch.

FIG. **4**A illustrates a top down plan view of a micro droplet switch according to another embodiment. This embodiment uses two droplets located on a coplanar waveguide.

FIG. **4**B illustrates a three-dimensional perspective view of the micro droplet switch of FIG. **4**A.

FIG. **4**C illustrates a magnified view of the signal electrode from a portion of the micro droplet switch of FIG. **4**B.

FIG. **4**D illustrates a three-dimensional perspective view of the micro droplet switch of FIG. **4**A containing two liquid droplets.

FIG. **5**A illustrates a top down plan view of a micro droplet switch according to another embodiment.

FIG. **5**B illustrates a magnified view of the dashed region α illustrated in FIG. **5**A showing the plurality of resistive elements.

FIG. **6**A illustrates a schematic representation of the electrical contact made between the liquid droplet and the signal electrode when the droplet contact line is located at position "A" in FIG. **5**B.

FIG. **6**B illustrates a schematic representation of the electrical contact made between the liquid droplet and the signal electrode when the droplet contact line is located at position "B" in FIG. **5**B.

FIG. **6**C illustrates a schematic representation of the electrical contact made between the liquid droplet and the signal electrode when the droplet contact line is located at position "C" in FIG. **5**B.

FIG. **7** illustrates a top down plan view of a micro droplet switch according to another embodiment. In this embodiment, a heater element is disposed under the upper surface of substrate that is configured to heat the dielectric layer.

FIG. **8** is a graph of the contact angle and distance moved as a function of time for two different actuation voltages (75V and 100V).

FIG. **9**A is a graph of the actuation voltage (V) and signal voltage (V) as a function of time for a micro droplet switch. The on latency is around 60 μs and the off latency is around 150 μs.

FIG. **9**B is another graph of the actuation voltage (V) and signal voltage (V) as a function of time for a micro droplet switch. FIG. **9**B illustrates a rise/fall time of less than 5 μs with no bounce in signal.

FIG. **10** illustrates an illustrative method of making a micro droplet switch according to one aspect of the invention.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

FIGS. **1A** and **1B** illustrate a cross-sectional view of a micro droplet switch **10** according to one embodiment. In FIG. **1A**, the micro droplet switch **10** is in an "off" state while FIG. **1B** illustrates the micro droplet switch **10** in an "on" state. The micro droplet switch **10** includes a substrate **12** having an upper surface **14** on which a liquid droplet **16** rests. The micro droplet switch **10** further contains a frame **18** that disposed on or over the upper surface **14** of the substrate **12**. As explained herein, the frame **18** maintains the liquid droplet **16** in substantially the same location during actuation of the micro droplet switch **10**. A cap **20** is also illustrated in FIG. **1A** which is secured to the upper portion of the frame **18**. The micro droplet switch **10** may include one or more additional side walls or the like (not shown) that are located external to the frame to further contain the liquid droplet **16** in a closed environment.

In one embodiment, the substrate **12** is a multilayer substrate that includes a base layer **22** that may be formed from, for example, silicon or glass. A dielectric layer **24** is formed above the base layer **22** and includes one or more actuation electrodes **26**. The dielectric layer **24** may include a dielectric material such as SiO_2 or Si_3N_4. The one or more actuation electrodes **26** may be formed from electrical conductive materials such as metals. For example, the one or more actuation electrodes **26** may be formed from chromium or nickel. The one or more actuation electrodes **26** are operatively coupled to drive circuitry (now shown in FIGS. **1A** and **1B**) which is configured to apply a driving voltage. The driving voltage is a rapid increase (or decrease) in voltage that is applied to the one or more actuation electrodes **26**. The driving voltage is generally below 200V but the invention is not limited to the magnitude of the particular driving voltage.

Still referring to FIGS. **1A** and **1B**, the upper surface **14** of the substrate **12** includes a contact electrode **30** and a signal electrode **32**. The contact electrode **30** and the signal electrode **32** carry the respective signal that is to be switched "on" or "off" by the micro droplet switch **10**. For instance, while not shown in FIGS. **1A** and **1B**, the contact electrode **30** may be electrically coupled to an input while the signal electrode **32** may be electrically coupled to an output. The signal that is modulated by the micro droplet switch **10** may include direct current, alternating current, RF power, etc. In one aspect of the invention, the contact electrode **30** may actually be one of a plurality of signal electrodes **32**. For example, the switch **10** may be closed when the droplet **16** contacts two signal electrodes **32**, one of which is referred to as the contact electrode **32** because the droplet **16** is in constant contact during operation of the switch **10**. The contact electrode **30** and the signal electrode **32** may be made from an electrically conductive material such as, for instance, chromium or nickel although other materials are also contemplated to fall within the scope of the invention. Both the contact electrode **30** and the signal electrode **32** include at least a portion thereof that is exposed to the interior of the micro droplet switch **10**. In this regard, the liquid droplet **16** makes electrical contact with the respective contact electrode **30** and signal electrode **32** when contact is made.

The upper surface **14** (except for the contact electrode **30** and signal electrode **32**) may be coated with a hydrophobic coating **36** such as polytetrafluoroethylene (PTFE). The coating **36** reduces friction between the liquid droplet **16** and the upper surface **14** of the substrate **20**. In another aspect of the invention, the upper surface **14** of the substrate **12** may be optionally patterned to reduce the surface tension formed between the liquid droplet **16** and the upper surface **14** which may aid in increasing the switching speed of the micro droplet switch **10**.

The micro droplet switch **10** includes frame **18** that is disposed on or above the upper surface **14** of the substrate **12**. In this aspect, the frame **18** is formed on or is otherwise built up or bonded to the substrate **12**. However, it is also possible that the frame **18** is formed as part of or is connected to the upper cap **20** of the micro droplet switch **10**. The frame **18** may be made of a number of materials typically used in semiconductor or microfluidic applications such as, for instance, photoresist such as SU-8. As explained herein, the frame **18** is used to restrict free movement of the liquid droplet **16** on the upper surface **14** of the substrate **12**. The frame **18** may include a plurality of walls or posts that are formed to constrain translational movement of the liquid droplet **16**. While the frame **18** is used to constrain displacement or translation of the entire liquid droplet **16**, in some embodiments, the frame **18** is used to define both an active meniscus **40** and a non-active meniscus **42**.

The active meniscus **40** is the portion of the meniscus of the liquid droplet **16** that is moved by the actuation electrode(s) **26** to complete the circuit between the contact electrode **30** and the signal electrode **32** upon actuation of the micro droplet switch **10**. The non-active meniscus **42** is the portion of the meniscus of the liquid droplet **16** that is not moved by the by the actuation electrode(s) **26** during switch operation. The active meniscus **40** and the non-active meniscus **42** are defined by a number of openings or apertures **44** in the frame **18** (illustrated in FIGS. **2A** and **2B**). FIGS. **2A** and **2B** illustrate an aperture **44***a* which forms the active meniscus **40** and aperture **44***b* which forms the non-active meniscus **42**. As explained in more detail below, the non-active meniscus **42** may act as a buffering meniscus that compensates for variations in the volume of the liquid droplet **16** that is placed on the micro droplet switch **10**.

The liquid droplet **16** is formed from an electrically conductive material such that when the liquid droplet **16** contacts both the contact electrode **30** and the signal electrode **32**, the micro droplet switch **10** is closed and signal can pass from the contact electrode **30** through the liquid droplet **16** and into the signal electrode **32** (or vice versa as the case may be). In one aspect of the invention, the liquid droplet **16** includes a liquid metal such as mercury although other metals and alloys may also be used. As seen in the embodiment of FIGS. **1A** and **1B**, in both the "off" and "on" states, the liquid droplet **16** makes electrical contact with the contact electrode **30**. To close the micro droplet switch **10** only the active meniscus **40** needs to be moved a relatively short distance to make electrically contact. The liquid droplet **16** may be surrounded by dielectric fluid **48** that is immiscible with the liquid droplet **16**. This fluid **48** may be a liquid or a gas (e.g., oil or air).

As seen in FIG. **1A**, in the "off" state, a relatively small actuation gap **50** is formed between the contact line **52** of the liquid droplet **16** and the signal electrode **32**. The contact line **52** refers to the peripheral interface between the liquid droplet **16** and the upper surface **14** of the substrate **12**. In one aspect of the invention, the actuation gap **50** is less than around 100 μm in length, and in some instances, as small as about 10 μm in length. In addition, the actuation gap **50** preferably is stable in that over many cycles of the micro droplet switch **10** the actuation gap **50** remains substantially constant in the "off" state.

FIG. **1**B illustrates the micro droplet switch **10** in the "on" state after an actuating voltage has been applied to the underlying actuation electrode **26** located on the right hand side of FIG. **1**B. Actuation of the electrode **26** causes the active meniscus **40** and thus the contact line **52** to move to the right until the liquid droplet **16** comes into physical contact with the signal electrode **32**. The switch is turned back to the "off" state by de-energizing the electrode **26**. When the electrode **26** is not powered, the liquid droplet will naturally revert back to the state illustrated in FIG. **1**A. The switching process can, of course, continue as explained above for any number of additional cycles. The left most actuation electrode **26** is optional and may be used to assist in pulling the liquid droplet **16** back into its resting state. For example, in some micro droplet switches **10** the "off latency" or the amount of time needed to open the switch after de-energizing the actuation electrode **26** (right hand side one in FIGS. **1**A and **1**B) is longer than the "on latency" or the amount of time needed to close the switch after energizing the actuation electrode **26**. In order to reduce the "off latency" time, an actuation electrode **26** may be activated to assist the liquid droplet **16** to return back to the resting state illustrated in FIG. **1**A.

FIGS. **2**A and **2**B illustrate another embodiment of a micro droplet switch **10**. FIG. **2**A illustrates the micro droplet switch **10** in an "off" state while FIG. **2**B illustrates the micro droplet switch **10** in an "on" state. As seen in FIGS. **2**A and **2**B, the frame **18** is formed with two different sized openings **44***a*, **44***b*. The smaller of the two openings **44***a* forms the active meniscus **40** while the larger aperture **44***b* located on the opposing side of the frame **18** forms the non-active meniscus **42** which acts as a buffering meniscus. As seen in FIGS. **2**A and **2**B, the liquid droplet **16** is constrained within the frame **18** thereby preventing free movement of the liquid droplet during activation of the micro droplet switch **10**.

Referring now to FIG. **2**A, an actuation gap **50** is formed between the active meniscus **40** (or contact line **52**) and the signal electrode **32**. This actuation gap **50** is substantially constant when the micro droplet switch **10** is in the "off" state as illustrated in FIG. **2**A. The substantially constant actuation gap **50** is also maintained by the use of the buffering meniscus **42**. The radius of curvature of the active meniscus **40** is smaller than the radius of curvature at the buffering meniscus **42**. The buffering meniscus **42** has the advantageous property that it can adjust for changes in volumes of the liquid droplet **16** that is applied to the micro droplet switch **10**. For example, if too much or too little droplet material is deposited, the excess or shortage of material will be accommodated by changes in the buffering meniscus **42** which will not affect the active meniscus **40**. In this regard, even if too much (or too little) material for the liquid droplet **16** is deposited, the actuation gap **50** remains constant. This is significant because with prior switch designs it was difficult to accurately deposit the correct amount of droplet material in the switch. Also, as seen in FIGS. **2**A and **2**B, accurate positioning of the liquid droplet **16** is achieved by the constrained configuration that holds the liquid droplet **16** in the proper location relative to the contact electrode **30** and signal electrode **32**.

FIGS. **2**A & **2**B also illustrate a second optional actuation electrode **28** that, as explained above, may be used to reduce the off latency of the micro droplet switch **10**. The second actuation electrode **28** may be activated after the main actuation electrode **26** has been de-energized so that the liquid droplet **16** can more rapidly return to the state illustrated in FIG. **2**B. Of course, the second actuation electrode **28** is optional and may be omitted entirely. FIGS. **2**A and **2**B also illustrate the drive circuitry **56** that is used to apply a driving voltage to the actuation electrode **26**. In some instances the actuation voltage applied by the drive circuitry **56** may be a positive voltage while in other instances it may be a negative voltage.

FIGS. **3**A, **3**B, and **3**C illustrate another embodiment of a micro droplet switch **10**. Referring to FIG. **3**A, which illustrates a top-down plan view, the micro droplet switch **10** includes four posts or pillar structures that makeup the frame **18**. The frame **18** in this embodiment is substantially symmetrical and there are no different sized openings although in other alternative embodiments the frame **18** may utilize different sized openings as described above to take advantage of the buffering meniscus. Still referring to FIG. **3**A, the micro droplet switch **10** includes three signal electrodes **32***a*, **32***b*, **32***c* positioned about the periphery of the switch **10**. Multiple signal electrodes **32***a*, **32***b*, **32***c* may be particularly useful for switching relatively large currents. In addition, as seen in FIG. **3**A, the three signal electrodes **32***a*, **32***b*, **32***c* terminate in a pointed tip. In this embodiment, the actuation electrode **26** is made from a circular electrode that is disposed inside the dielectric layer **24** (e.g., Si_3N_4) disposed above base layer **22**. The contact electrode **30** in this embodiment is disposed on the upper surface **14** of the substrate **12** in a circular shape and acts as a ground electrode. In some instances, the ground electrode **30** may be disposed beneath the upper surface **14** of the substrate **12**. As seen in FIGS. **3**A and **3**B, the drive circuitry **56** couples the actuation electrode **26** with the contact electrode **30**.

FIG. **3**B illustrates a cross-sectional view of the micro droplet switch of FIG. **3**A taken along the line A-A' (with frames removed for clarity purposes). A first liquid droplet **16***a* is illustrated in the quiescent or "off" state while a second liquid droplet **16***b* is illustrated in the "on" state. As seen in FIG. **3**B, in the "off" state the liquid droplet **16***a* only contacts the contact electrode **30** (e.g., ground electrode). This can be seen by the contact line **52** which does not touch any of the signal electrodes **32***a*, **32***b*, **32***c*. However, when the underlying actuation electrode **26** is activated, the contact line **52** of the liquid droplet **16** expands outward until the liquid droplet **16***b* makes electrical contact with the signal electrodes **32**. Preferably, the configuration of the multiple signal electrodes **32***a*, **32***b*, **32***c* is such that contact is made at substantially the same time. As also seen in FIG. **3**B, with the exception of the contact electrode **30** and the signal electrodes **32***a*, **32***b*, **32***c*, the upper surface **14** of the substrate **12** contains a coating **36** of PTFE or the like. FIG. **3**C illustrates a three dimensional image of the micro droplet switch **10** of FIGS. **3**A and **3**B.

In the micro droplet switch **10** of FIGS. **3**A-**3**C, the high surface tension of the liquid droplet **16** ensures that the same is accurate positioned and enables small actuation gaps **50**. For a given volume of droplet fluid, any variation in the base radius (contact line **52** position) due to hysteresis is accompanied by a change in the spherical radius of the liquid droplet **16**. However, the frame **18** restricts the change in the spherical radius of the liquid droplet **16**. Thus, any variation in the contact line **52** position due to hysteresis can only be possible through a variation in the local curvature. The variation in the local curvature gives rise to a restoring Laplace pressure which resists the change in the position of the contact line **52**.

The above-described micro droplet switch **10** is able to be implemented in so-called "hot switch" applications where the signal between the contact electrode **30** and the signal electrode **32** remains on during the switching application. This is particularly advantageous for RF applications. The micro droplet switch **10** also exhibits excellent durability and stability. Because the liquid droplet **16** is securely contained within the micro droplet switch **10** via the frames **18**, vibration stability up to about 16 G is possible. Of course, other switch designs can exhibit even better stability.

FIGS. **4**A, **4**B, and **4**C illustrate another embodiment of a micro droplet switch **60** that includes first and second droplets **61***a*, **61***b*. In this embodiment, a substrate **62** is configured as a coplanar waveguide having a first ground portion **64**, a second ground portion **66**, and a signal portion **68** interposed between the first and second ground portions **64**, **66**. The coplanar waveguide thus configured as a standard GSG coplanar waveguide. The first ground portion **64** includes a ground electrode **70** disposed on a surface thereof In a similar manner, the second ground portion **66** includes a ground electrode **72** disposed on a surface thereof The ground electrodes **70**, **72** are disposed in such a manner that a liquid droplets **61***a*, **61***b* are always in electrical contact with their respective ground electrodes **70**, **72**. The signal portion **68** of the coplanar waveguide substrate **62** is operatively coupled to a first signal electrode **74** and a second signal electrode **76**. As best seen in FIG. **4**A, a first actuation electrode **78** is located beneath the upper surface **63** adjacent to the first ground portion **64**. A recessed portion may optionally be formed in the first ground portion **64** in which the actuation electrode **78** is disposed. The actuation electrode **78** is operatively coupled to driving circuitry (not shown) configured to apply a driving voltage. A second actuation electrode **80** is located beneath the upper surface **63** adjacent to the second ground portion **66** and is also operatively coupled to driving circuitry (not shown) configured to apply a driving voltage. The second actuation electrode **80** may optionally be disposed in a recessed portion formed in the second ground portion **66**.

As best seen in FIGS. **4**A and **4**B, the micro droplet switch **60** includes two separate frames **82**, **84** for holding the respective droplets **61***a*, **61***b*. The frames **82**, **84** form two separate enclosures for the droplets **61***a*, **61***b*. The frames **82**, **84** may be formed as a series of walls patterned from a photoresist such as SU-8. In this embodiment, frame **82** includes two opposing openings **86***a*, **86***b* having different sizes so that an active meniscus and a buffering meniscus can be formed in the liquid droplet **61***a* as described herein. Similarly, frame **84** includes two opposing openings **88***a*, **88***b* having different sizes.

FIG. **4**C illustrates a magnified view of one of the signal electrodes **74** electrically coupled to the signal portion **38** of the substrate **62**. The signal electrode **74** includes a sharpened tip although other configurations may be employed in the micro droplet switch **60**. The opposing signal electrode **76** (not magnified in FIG. **4**C) is configured in a similar manner.

The micro droplet switch **60** of FIGS. **4**A-**4**C is particularly useful as a shunt switch although the particular implementation of the switch **60** is not limited to shunt switches. In a shunt switch, the switch is open until the signal electrode is electrically coupled to the ground electrode. In the micro droplet switch **60** described above, the switch is opened by activation of the two actuation electrodes **78**, **80** at substantially the same time. When the actuation electrodes **78**, **80** are driven with an actuating voltage, the active portions of the droplets **61***a*, **61***b* are drawn toward the signal portion **68** of the switch **60** until the droplets **61***a*, **61***b* make contact with their respective signal electrodes **74**, **76**. When the droplets **61***a*, **61***b* connect the ground electrodes **70**, **72** with their respective signal electrodes **74**, **76** the switch is open because the signal portion **68** is at the same potential as the ground electrodes **70**, **72**. By using the two droplet configuration, this design solves capacitance leak that would otherwise occur from leakage of charges from the signal line to the ground line via the actuation electrode. In the micro droplet switch **10** of FIGS. **4**A-**4**C overall capacitive leakage during the "off" state is reduced. The micro droplet switch **10** has been modeled using commercially available finite element analysis software (High Frequency Structure Simulator—HFSS) which simulated a better than 0.2 dB insertion loss up to 40 GHz of operation.

FIGS. **5**A and **5**B illustrate another alternative aspect of the invention. In this embodiment, a plurality of resistive elements **92***a*, **92***b* are coupled to the signal electrode **32**. The plurality of resistive elements **92***a*, **92***b* provide a stepped increase (or decrease in other cases) in the resistance of the signal path between the contact electrode **30** and the signal electrode **32**. This embodiment may be particularly useful in high power switching applications where arcing is a concern. By progressively stepping the resistance to a higher level during switch deactivation (or activation), the potential to cause arcing is reduced. While FIG. **5**B illustrates two restive elements **92***a*, **92***b*, in other embodiments there could be a single resistive element **92** or more than two.

FIG. **5**A illustrates a switch **10** of the type illustrated in FIGS. **3**A and **3**B although the resistive elements **92***a*, **92***b* may be used in other embodiments described herein. FIG. **5**A illustrates a dashed region that encompasses the interface of a signal electrode **32***a* and an upper surface **14** of the switch substrate **12**. FIG. **5**B also illustrates movement of the contact line **52** formed by a droplet as the switch **10** is deactivated (i.e., opened). Thus, in FIG. **5**B the droplet initially has a contact line illustrated by A, then moves to position B, and then to position C, and then finally is out of contact with the signal electrode **32***a*.

As seen in FIG. **5**B, the resistive elements **92***a*, **92***b* comprise a resistive path that couples to the signal electrode **32***a*. The resistive element **92***a*, **92***b* may be patterned on an upper surface **14** of the substrate **12** using conventional semiconductor processes. In one embodiment, the resistance is stepped up in an increasing fashion as the switch is turned off by de-energizing the actuation electrode **26**. For example, with reference to FIG. **5**B, the contact line **52** identified as "A" indicates a state wherein the liquid droplet **16** contacts both resistive elements **92***a*, **92***b*, as well as the signal electrode **32***a*. The electrical schematic of this configuration is illustrated in FIG. **6**A. In this configuration, the switch is in the fully "on" state.

When the micro droplet switch **10** is turned off, the liquid droplet **16** begins to restore to its original configuration. The contact line **52** identified in FIG. **5**B as "B" illustrates movement of the droplet away from the contact electrode **32**A. Electrically contact is still made to the signal electrode **32***a* but at an increased resistance because of the two resistive elements **92***a*, **92***b*. The electrical schematic of this configuration is illustrated in FIG. **6**B. **R2** is open and current passes through **R1** and **R3**. The liquid droplet **16** continues to move back to its original configuration. The contact line **52** identified in FIG. **5**B as "C" illustrates additional movement of the droplet away from the contact electrode **32**A. Electrically contact is made to the signal electrode **32***a* at an increasing resistance by passing through resistive element **92***a* (but not resistive element **92***b*). The electrical schematic of this configuration is illustrated in FIG. **6**C. **R1** and **R2** are open and current passes only through **R3**. Eventually, the liquid droplet **16** is electrically disconnected from the signal electrode **32***a* completely.

FIG. **7** illustrates another embodiment of a micro droplet switch **10**. In this embodiment, a heating element **96** is located underneath the upper surface **14** of the substrate **12**. For example, the heating element **96** (or multiple heating elements) may be placed between the dielectric layer **24** and the coating layer **36** (e.g., PTFE). The heating element **96** may be formed as a resistive heating element that emits heat upon the application of electrical current. The heating element **96** is used to discharge the dielectric layer **24** of charges. This may lead to longer switch life. While FIG. **7** illustrates the heating element **96** in a micro droplet switch **10** of the type illustrated in FIGS. **3**A and **3**B, the heating element **96** may be incorporated into other switch embodiments described herein.

The fast switching times of the micro droplet switches **10**, **60** described herein is produced not only by the small actuation gap **50** but also the speed of the active meniscus **40**. FIG. **8** illustrates a graph of contact angle and distance moved (active meniscus) for different actuation voltages (75V and 100V). As seen in the data for the distance moved, the speed is very rapid during the time when the contact angle is changing just after actuation and begins to level or taper off as time progresses. The above-described micro droplet switches **10**, **60** utilize the initial high speeds (e.g., ~40-50 cm/s) that are generated just after actuation to close the actuation gap **50**.

FIGS. **9**A and **9**B illustrate the performance characteristics of the micro droplet switch **10** after actuation of the actuation electrode **26**. FIG. **9**A illustrates an "on latency" of around 60 μs after electrode **26** actuation. It should be noted, however, that on latency values of less than about 50 μs have been obtained using micro droplet switch configurations described herein. This is approximately 20× faster than the switching times reported by others. FIG. **9**A also illustrates that there is no signal bounce after the micro droplet switch **10** has been closed. FIG. **9**A also illustrates the "off latency" of the micro droplet switch **10** after the actuation electrode **26** has been turned off. The off latency is around 150 μs. FIG. **9**B illustrates the rise/fall time of the micro droplet switch **10** in response to the application of the actuation voltage (100V). As seen in FIG. **9**B, the rise fall time is less than 5 μs with no bounce in signal.

FIG. **10** illustrates a process of fabricating a micro droplet switch **10**. Specifically, FIG. **10** illustrates a process of illustrating a micro droplet switch **10** of the type illustrated in FIGS. **2**A and **2**B although the processes described herein may also be used for other embodiments of the micro droplet switches. The left side of FIG. **10** illustrates the fabrication of the micro droplet switch **10** along the line A-A' in FIG. **2**A while the right side of FIG. **10** illustrates the fabrication of the micro droplet switch **10** along the line B-B' in FIG. **2**A. Generally, the fabrication process is a multi-step lithography process in which the various features are built on or in the substrate **12**. As seen in operation **1000** of FIG. **10**, chromium is deposited on a base layer **22** (e.g., glass) using, for example, e-beam deposition. The deposited chromium is then patterned and wet etched in chromium photomask etchant to form the actuation electrodes **26**. Next, in operation **1100** a 3500 Angstrom silicon nitride dielectric layer **24** is deposited using PECVD. The dielectric layer **24** is then patterned and etched using reactive ion etching (RIE) to open the contact pads.

As seen in operation **1200**, lift-off nickel is used to form the contact electrode **30** and the signal electrode **32**. Nickel is used because it is one of the few metals that does not chemically react with mercury, which is used for the liquid droplet **16**. Alternatively, chromium may be used but its surface oxidation can lead to excessive contact resistance. Next, in operation **1300**, a multi-coat SU-8 process is used to form 500 μm high frames **18**. Because a long, continuous exposure required to heat the relatively thick SU-8 layer causes hardening of the resist due to heating, the process is broken up into a series of heating/cooling steps. In particular, the total exposure time was broken into steps of 30 seconds with 30 seconds of cooling between subsequent exposures. In operation **1400** a hydrophobic coating **26** (e.g., PTFE) is then spin coated on the upper surface **14** of the substrate **20**. This hydrophobic coating **26** is then patterned and etched using O_2 plasma. While not illustrated in FIG. **10**, a liquid droplet **16** is then deposited on the micro droplet switch **10**. For example, the liquid droplet **16** may include a 600 μm diameter mercury droplet that is placed on the micro droplet switch **10** using a pipette or the like. A cap **20** (not shown in FIG. **10**), can then be adhered to the upper surface of the frame **18** to enclose the liquid droplet **16**.

The micro droplet switches **10**, **60** described herein enable fast mechanical-based switches. These micro droplet switches **10**, **60** may be particularly useful in RF switching applications such as base stations, radar devices, or even mobile devices although the invention is not limited to any particular application. The micro droplet switches **10**, **60** may also be particularly suited for "hot switching" applications.

While embodiments of the present invention have been shown and described, various modifications may be made without departing from the scope of the present invention. The invention, therefore, should not be limited, except to the following claims, and their equivalents.

What is claimed is:

1. A switch comprising:

a substrate having an upper surface containing at least one signal electrode;

at least one actuation electrode disposed beneath the upper surface of the substrate; the at least one actuation electrode operatively coupled to drive circuitry; and

a frame disposed on or above the upper surface of the substrate and configured to hold a droplet in substantially the same location during actuation of the switch, wherein the frame includes a first opening configured to define a first portion of the droplet meniscus and a second opening configured to define a second portion of the droplet meniscus, wherein the second opening is larger than the first opening.

2. The switch according to claim **1**, wherein the frame is disposed at a predetermined location relative to the at least one signal electrode.

3. The switch according to claim **1**, wherein the droplet comprises a conductive liquid, the droplet being surrounded by a dielectric fluid that is immiscible with the droplet.

4. The switch according to claim **1**, wherein when the switch is a non-actuated state, the frame maintains a substantially constant gap between a contact line of the droplet and the at least one signal electrode.

5. The switch according to claim **4**, wherein the substantially constant gap is a distance within the range of less than 100 μm.

6. The switch according to claim **4**, wherein during actuation, a contact line of the droplet moves initially at a first speed and later at a second speed slower than the first speed and wherein the droplet contacts the at least one signal electrode when moving at the first speed.

7. The switch according to claim **1**, wherein the switch has an on latency of less than about 50 μs.

8. The switch according to claim **1**, wherein the switch has a rise/fall time of less than about 5 μs.

9. The switch according to claim **1**, further comprising a ground electrode disposed on or beneath the upper surface of the substrate, the ground electrode being operatively coupled to drive circuitry.

10. The switch according to claim **1**, further comprising a second signal electrode disposed on the upper surface of the substrate.

11. The switch of claim **1**, further including a heater configured to heat the switch.

12. The switch of claim **11**, wherein the heater comprises at least one heating element disposed beneath the upper surface of the substrate, the at least one heating element being configured to heat a dielectric layer of the substrate.

13. The switch of claim **1**, wherein the signal electrode comprises a plurality of resistive elements, wherein each resistive element is selectively engaged by a moving contact line of the droplet.

14. The switch of claim **1**, wherein one of the signal electrodes comprises a contact electrode, wherein the droplet is in electrical contact with the contact electrode at all times during switch actuation.

15. The switch of claim **1**, wherein the frame comprises a plurality of walls or posts formed on the substrate and in contact with the droplet, wherein the plurality of walls or posts constrain translation of the droplet.

16. A switch comprising:

a substrate configured as a coplanar waveguide having a first ground portion, a signal portion, and a second ground portion, the first and second ground portions including respective ground electrodes, the signal portion being operatively coupled to first and second signal electrodes;

a first actuation electrode disposed beneath the upper surface of the substrate adjacent to the first ground portion, the first actuation electrode operatively coupled to drive circuitry;

a second actuation electrode disposed beneath the upper surface of the substrate adjacent to the second ground portion, the second actuation electrode operatively coupled to drive circuitry; and

a first frame disposed on or above an upper surface of the substrate and configured to hold a first droplet in substantially the same location over the first ground portion;

a second frame disposed on or above an upper surface of the substrate and configured to hold a second droplet in substantially the same location over the second ground portion; and

wherein actuation of the first and second actuation electrodes electrically connects the first droplet with the first signal electrode and electrically connects the second droplet with the second signal electrode.

17. The switch according to claim **16**, wherein when the switch is in a non-actuated state, the first frame maintains a substantially constant gap between a contact line of the first droplet and the first signal electrode and the second frame maintains a substantially constant gap between a contact line of the second droplet and the second signal electrode.

18. The switch according to claim **17**, wherein the substantially constant gap is a distance within the range of less than 100 μm.

19. The switch according to claim **17**, wherein the first frame includes a first opening configured to define a first portion of the first droplet meniscus and a second opening configured to define a second portion of the first droplet meniscus, wherein the second opening is larger than the first opening and wherein the second frame includes a first opening configured to define a first portion of the second droplet meniscus and a second opening configured to define a second portion of the second droplet meniscus, wherein the second opening is larger than the first opening.

20. The switch of claim **16**, further including a heater configured to heat the switch.

21. The switch of claim **20**, further comprising at least one heating element disposed beneath the upper surface of the substrate, the at least one heating element being configured to heat a dielectric layer of the substrate.

22. The switch of claim **16**, wherein one or both of the first and second signal electrodes comprises a plurality of resistive elements, wherein each resistive element is selectively engaged by a moving contact line of the respective droplets.

23. A method of switching comprising:

providing a switch comprising a substrate having an upper surface containing at least one signal electrode, the switch including at least one actuation electrode disposed beneath the upper surface of the substrate and operatively coupled to drive circuitry, the switch further comprising a frame disposed on or above the upper surface of the substrate and configured to hold a droplet, wherein the frame is configured to produce a droplet having a first meniscus portion with a smaller radius of curvature than a second meniscus portion, the first meniscus portion forming a contact line that is moveable to selectively engage the at least one signal electrode;

activating the at least one actuation electrode to move a contact line of the droplet in electrical contact with the signal electrode, wherein the droplet remains in substantially the same location during actuation of switch and wherein the contact line of the droplet is in electrical contact with the signal electrode within 50 μs of activating the at least one actuation electrode.

24. The method of claim **23**, further comprising heating the switch.

25. The method of claim **23**, further comprising deactivating the at least one actuation electrode to move the contact line of the droplet formed with the surface away from the at least one signal electrode.

26. The method of claim **23**, wherein during actuation, a contact line of the droplet moves initially at a first speed and later at a second speed slower than the first speed and wherein the droplet contacts the at least one signal electrode when moving at the first speed.

27. A switch comprising:

a substrate having an upper surface containing at least one signal electrode;

at least one actuation electrode disposed beneath the upper surface of the substrate; the at least one actuation electrode operatively coupled to drive circuitry;

a frame disposed on or above the upper surface of the substrate and configured to hold a droplet in substantially the same location during actuation of the switch; and

a heater configured to heat the switch, wherein the heater comprises at least one heating element disposed beneath the upper surface of the substrate, the at least one heating element being configured to heat a dielectric layer of the substrate.

28. A switch comprising:

a substrate having an upper surface containing at least one signal electrode;

at least one actuation electrode disposed beneath the upper surface of the substrate; the at least one actuation electrode operatively coupled to drive circuitry;

a frame disposed on or above the upper surface of the substrate and configured to hold a droplet in substantially the same location during actuation of the switch; and

wherein the signal electrode comprises a plurality of resistive elements, wherein each resistive element is selectively engaged by a moving contact line of the droplet.

* * * * *